

**AN INVESTIGATION  
INTO THE  
INSITU "U" VALUES OF WALL CONSTRUCTIONS**

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• A SONNET TO U

*Thermal conductivity is symbolised by  $K$   
And  $L$  the layer thickness  
(Measured the metric way).*

*By dint of mathematics and by virtue of persistence  
The  $L$  divided by the  $K$  will lead us to Resistance.  
To do this trick with cavities also we are not able  
So if you want resistance you have to use a table.  
Resistances at surfaces we also need to know  
Depending on exposure (in the case of  $R_{so}$ ).  
Upon the inside  $R_{si}$  may cause a little frown  
For it depends on heat flow going up or coming down.  
Now add up all resistances, divide them into one  
To calculate the 'U' value.  
Hooray the job is done!*

## **ABSTRACT**

### **AN INVESTIGATION INTO THE INSITU "U" VALUES OF WALL CONSTRUCTIONS**

The results of an insitu investigation into the thermal performance of a range of wall constructions are presented. The investigations were mainly undertaken to establish the uncertainty introduced by the measurement, the variability in the performance of the wall due to factors such as workmanship and the relevance of design values in practice. This study provides a useful addition to the otherwise sparse literature of actual measured heat flow and temperature data available from large scale field surveys in UK.

A review of methods and equipment used to recover the thermal transmittance value of wall constructions is presented. The Heat Flow Sensor measurement method was found to be most suitable for the needs of the study and was evaluated both theoretically and experimentally.

An experimental design approach was devised which enabled the separation of the variability involved in the measurement process and the variability involved in the performance of the wall to be obtained. The four generic wall types sampled included a representative range of existing and new build constructions. The indications are that the wall constructions investigated broadly perform as expected. However, for certain wall types there were significant differences between measured and standard design calculation values. This was because the appropriate theoretical model was not applied in order to establish the transmittance of the wall construction at the design stage.

It would appear that the overall error in the measurement process, which is a combination of both the systematic and the random error, was typically of the order of  $\pm 11\%$ , whereas the variability in the wall performance was seen to vary as a function of the wall type with the resulting values ranging between 4% and 39.5%. The differences in the observed performance of the wall may be potentially attributed to 4 major causes, namely:

(a) dimensional tolerances and material properties, (b) changes in material properties, (c) the wall as part of the construction and (d) workmanship.

The average wall performance in some circumstances can be estimated satisfactorily by using a one dimensional model where a relatively homogeneous wall construction is assumed. While the area weighted one dimensional model gives a reasonable estimate of the average wall performance by taking into account the cold bridging of the mortar joints, a more complete understanding of the wall performance can only be achieved by the use of a three dimensional model.

*Dedicated to*

*Joyce*

*for being a tower of strength and support*



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# **INTRODUCTION**

## **CHAPTER 1**



## **1.0 Study of wall performance**

This thesis is concerned with an investigation into the measurement of the insitu thermal transmittance of a range of wall constructions in a number of buildings in the North East of England. This is seen as being highly relevant given the importance of the "U" value in describing component performance and relates to such issues as appraising the effectiveness of energy conservation measures, calculating plant size and annual energy consumption and, not least, ensuring compliance with the Building Regulations.

This is an area which features in the EDC consultation document on "Strategy for Construction R & D" (NEDC - 1985) in which particular attention is drawn to the need to monitor the performance of whole buildings and major components in service to relate predicted performance to experience.

To place the work in a wider context the areas of Environmental Crisis, Energy Efficiency and Quality Assurance in Buildings are briefly reviewed before describing the nature of the investigation in greater detail.

### **1.1 The Environmental Crisis and Energy Efficiency**

Until the early 70s the industrialised world enjoyed inexpensive fuel, and energy conservation was, in general, rarely considered. Low capital cost tended to be the overriding consideration for building construction and it was uneconomic to use capital on energy conservation measures with its long pay back period.

Following the first energy crisis of 1973 and the ensuing energy debate, the economic fortunes of many countries have been transformed. In international terms the energy picture is a complex and changing one. Energy efficiency has become one of the important issues in the industrialised society.

Energy efficiency works. The world has saved energy worth \$300 billion (dollars) per year since 1973 when the price of oil escalated and forced energy planners to rethink their strategies. In the 21 countries belonging to the International Energy Agency founded in 1974 economic output grew on average by 32% between 1973 and 1986 and yet energy demand rose by just 5%. Results such as these, have dispelled the myth that rising energy consumption runs hand in hand with economic growth (Boyle - 1989).

Although the initial need was to save energy to conserve resources, the issue of Global Warming, the "Greenhouse Effect", has now come to the fore and it is realised that the use of fuel has worldwide consequences and cannot be considered as a solely national problem.

A report published as recently as April 1990 by the independent Watt Committee on Energy, indicates how industry and government could stabilise emissions of greenhouse gases at the levels produced in 1988, up to the year 2000. The year long study concludes with a package of short and long term measures which are broadly in line with the current policies of the European Community. It emphasized that buildings, in general, have a major role to play by "Saving energy in homes and businesses through tougher building standards on thermal insulation, efficient electrical appliances, low-energy lighting and controls" (Watts - 1990).

### **Energy efficiency in buildings**

A major contributory factor towards the need for energy efficiency in buildings is the reduction of the carbon dioxide (CO<sub>2</sub>) emissions.

A proper understanding of the relationship between energy efficiency in buildings and CO<sub>2</sub> emissions requires an analysis which takes account of the fuels used and how they are attributed to the various uses of energy such as space heating, lighting and water heating. Buildings consume more than 40% of the total demand for energy in most industrialised countries. In the northern hemisphere, three-quarters of the energy heats space and water (Henderson - 1989).

In the UK about half the total energy bill of £37 billion is for energy used in buildings, i.e. in building services. Even a 1% reduction in this, through R & D on building services and energy conservation would lead to a very considerable saving of over £150 million a year (NEDC - 1985).

Energy use in buildings is responsible for about half of total UK emissions of carbon dioxide, the most important of the "greenhouse gases" and 60% of this is associated with dwellings. Those emissions could be reduced significantly through applying energy efficiency measures which are cost-effective and use well proven techniques and materials (Fig. 1.1).

Henderson and Shorrocks in 1989, examined the emission of carbon dioxide, due to the burning of fossil fuels - from 1950 to the present both, globally and for the UK. They found that global emissions have risen dramatically. They went on to investigate the potential for reducing emissions in the UK by the use of energy efficiency measures in dwellings and found that two thirds of the potential savings they identified would result from improved insulation standards, with the remaining third due to improved appliance efficiencies (Anon. 1 - 1990).



DOMESTIC SECTOR CO<sub>2</sub> SAVINGS (MILLION TONNES)  
THROUGH COST-EFFECTIVE ENERGY EFFICIENCY MEASURES  
TOTAL REDUCTION 44 MILLION TONNES

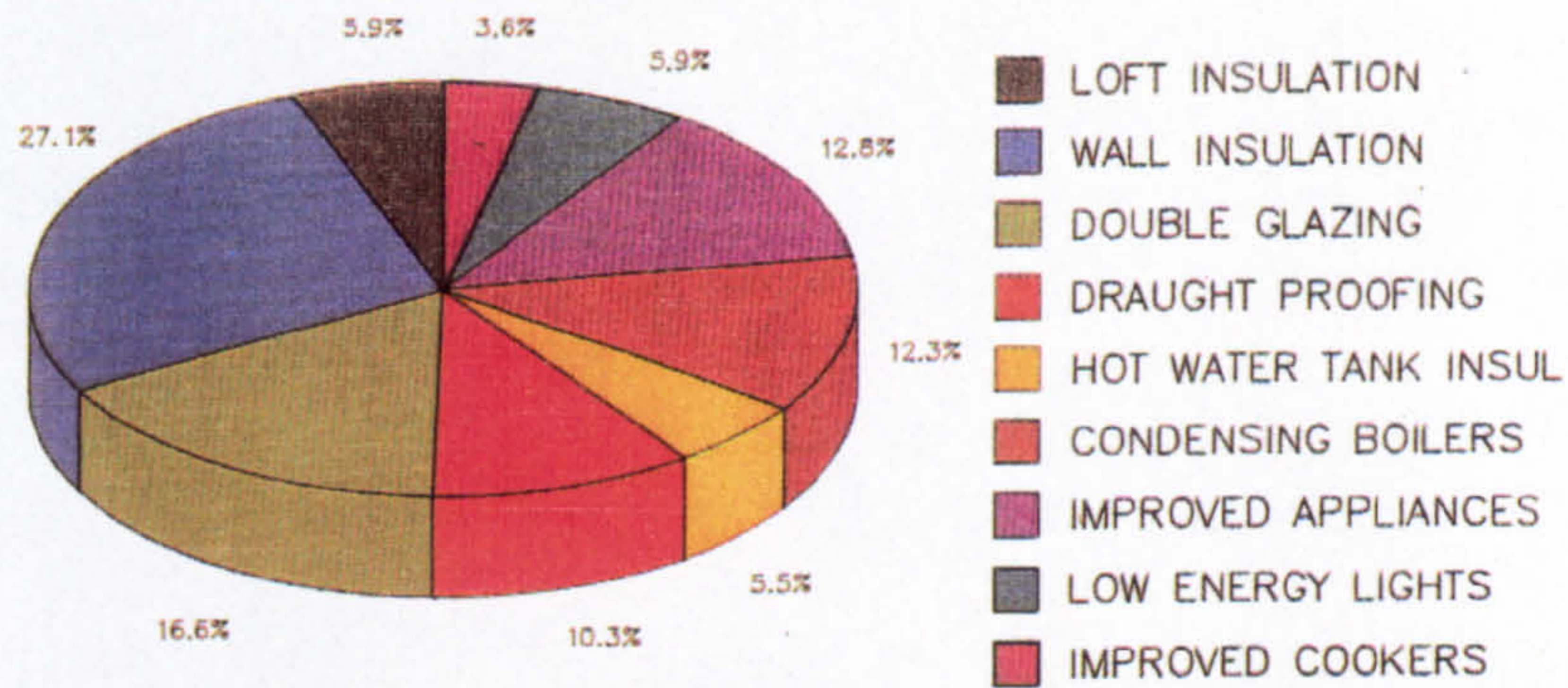


Fig. 1.1:

Domestic sector CO<sub>2</sub> savings through cost-effective energy efficiency measures

The Figure indicates the relative importance of different measures that could be applied cost-effectively. About two-thirds of the reduction in CO<sub>2</sub> is due to improved insulation, with cavity wall insulation and double glazing being the leading contributors. The other third is due to improved efficiency of heating systems, lighting and domestic appliances.

(After Henderson - 1989)

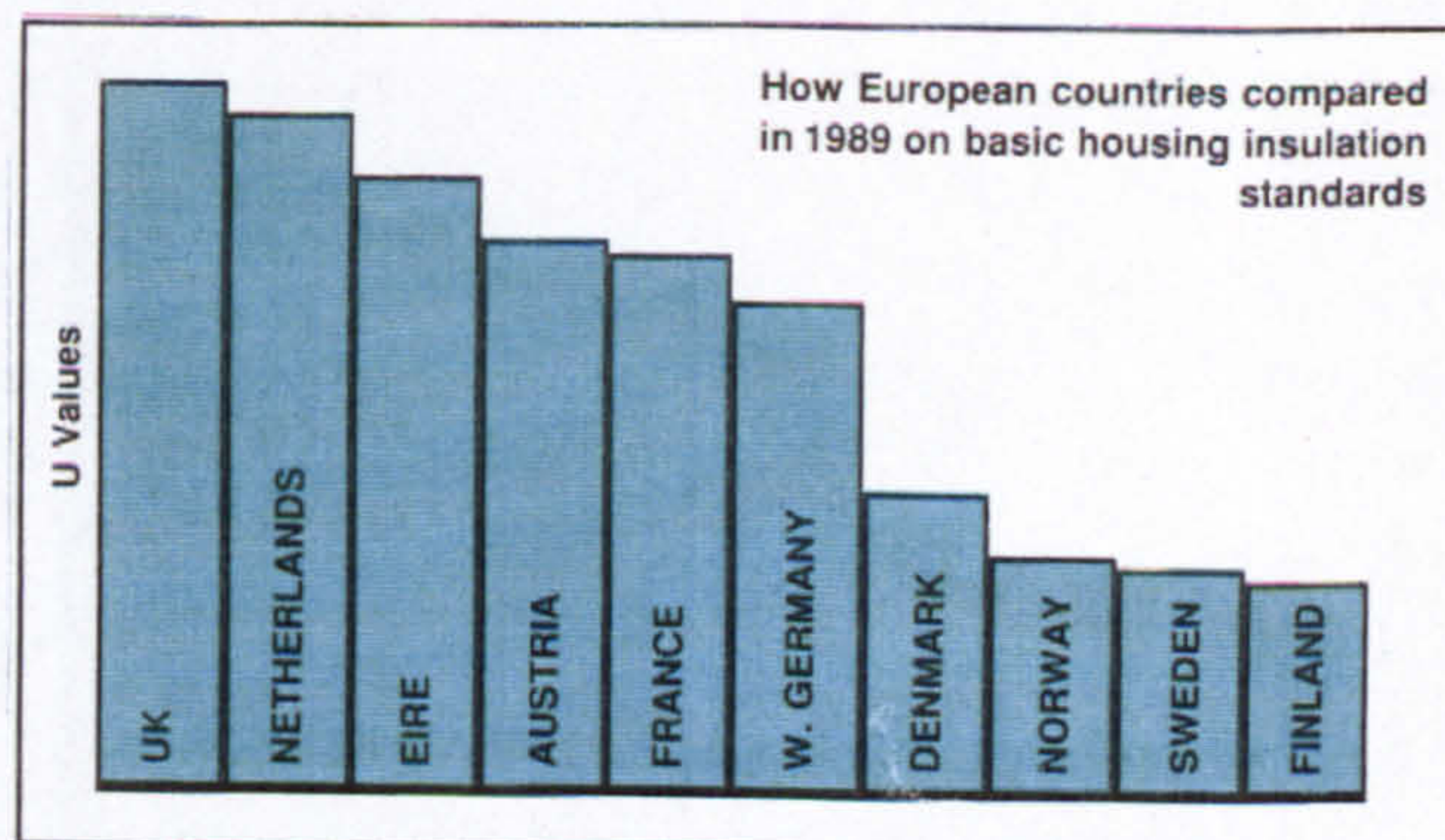


Fig. 1.2:

*U values in Europe (After Levinson et al - 1990)*



Energy efficiency measures can be applied equally effectively to both: existing building stock and new build.

In the case of existing building stock the potential of upgrading the thermal performance is significant, mainly by insulation improvements in the cavity walls and lofts, draught proofing and full double glazing. It is generally accepted that savings of 30% are technically possible in existing dwellings, i.e. 9% of all UK energy. If these savings are taken together with the low rate of building new housing, "it is apparent that energy conservation in existing housing is of considerable national importance" (Hildon and Davidson - 1989).

Knowing how the existing stock performs is essential, if the economic and environmental implications of upgrading the stock are to be fully appreciated and evaluated.

New buildings are designed and built to prescribed standards laid down in the Building Regulations. These exist to provide design standards and means for the prediction as to whether new buildings meet those standards. Part L of the 1990 Building Regulations for England and Wales requires improved thermal performance standards and energy savings for all new buildings by means mainly of higher standards of Thermal Insulation (Building Regulations - 1990). Consequently, the last ten years have seen a steady improvement in insulation standards for UK building. For example, mandatory standards contained in the Building Regulations for wall insulation have gone from U values of 1.0 to 0.45 W/m<sup>2</sup>K.

However, compared with Scandinavia and America, these improved standards still leave much to be desired. Indeed a recent analysis by Levinson et al (1990) indicated that UK still has the worst overall performance standards at the present time in Europe (Fig. 1.2).

However, in many countries insulation standards have now reached "super-insulation" levels as in Canada and the USA where there are some 30-40000 super-insulated houses. In the UK there is only a handful of buildings which approach these levels of performance. In the 21st century, homes are likely to be super-insulated buildings which have insulation thicknesses of typically 200mm in walls, 300mm in roofs and 100mm in floors, and they are more airtight. Careful control of the system helps to reduce heating bills by more than 80%, even for large houses in harsh climates (Boyle - 1989).

According to Henderson, head of energy, economics and statistics in the Building Energy Efficiency Division of Britain's Building Research Establishment, saving energy is "mainly a matter of doing a number of simple and relatively boring things well".

Even when designing to meet the Building Regulations in the UK, i.e. attaining the minimum level of performance, gives no guarantee that the building will perform in practice as predicted. There is evidence to suggest that the standards recommended by the Regulations

are sometimes not attained in practice (BEDC - 1987), it would be appear that we are not doing the simple and relatively boring things very well.

There is therefore a need to monitor buildings after they are erected, in order to establish their performance in practice. That is, some form of Quality Assurance assessment must be carried out.

## **1.2 Quality Assurance (QA) for buildings**

In recent years increasing concern has been expressed over the standard of work achieved in building construction. Defects in buildings, many of which could and should have been recognised and rectified during construction, have been costing hundreds of millions of pounds annually in remedial work (BEDC - 1987).

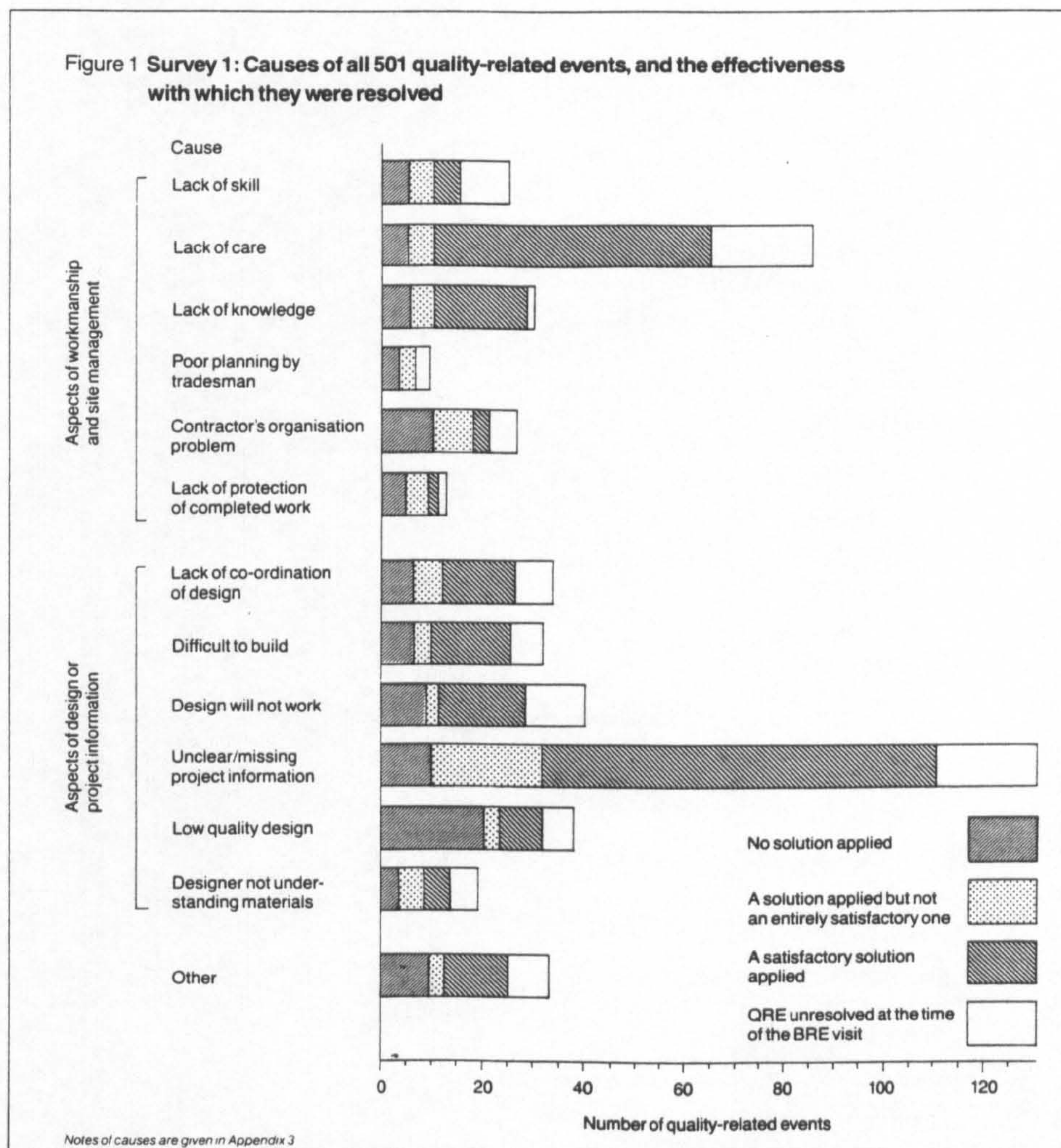
In a survey of 27 building sites in the public sector commissioned by the Building EDC, a number of common reasons were found. Figs 1.3 and 1.4 indicate that most faults were due mainly to design and construction and not due to the building product or component. A satisfactory solution can be applied in the majority of cases, but in a smaller proportion either no solution has been applied at all or a solution has been applied but not an entirely satisfactory one, leading to a loss of performance.

Repair and maintenance, at £11 billion now accounts for around 40% of construction activity compared with about 30% ten years ago (Fig. 1.5). Even a 1% reduction in repair and maintenance, because of better construction standards and improved durability, would effect a saving of over £100 million a year (NEDC - 1985).

The construction industry has come under pressure to adopt Quality Systems, mainly from three major sources (PSA - 1986):

- (a) Widespread client dissatisfaction with current building quality and performance, which has received considerable attention in the media and acts as a possible disincentive to people who might consider commissioning work.
- (b) Designers liability for defects resulting from negligence.
- (c) Major defects in the local authority housing stock estimated to require £3 billion to repair.

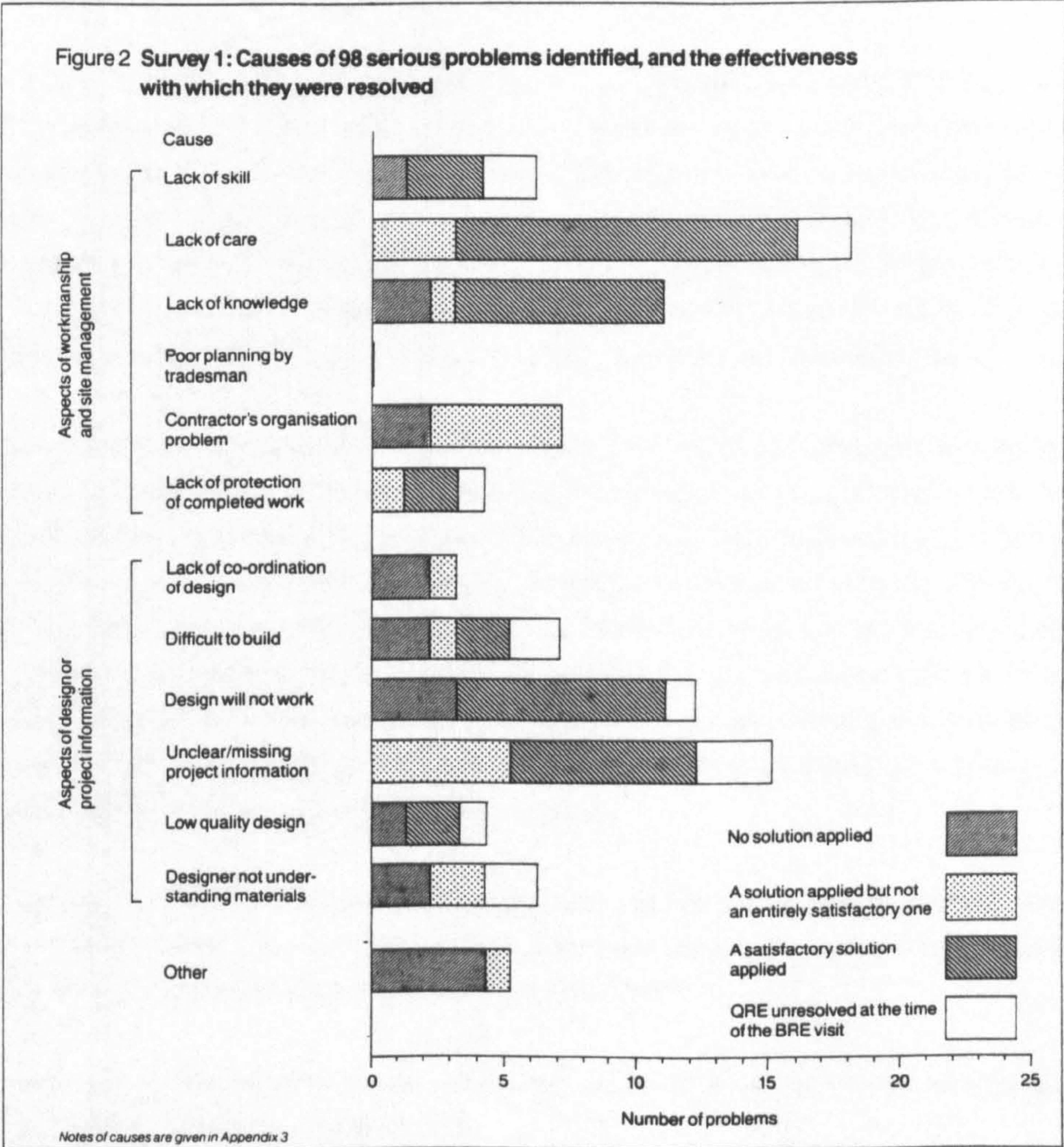




**Fig. 1.3:**

*Survey 1: Causes of all 501 quality-related events and the effectiveness with which they were resolved*  
(After BEDC - 1987)





**Fig.1.4:**  
*Survey 1: Causes of 98 serious problems identified and the effectiveness with which they were resolved*  
(After BEDC - 1987)



The application of QA procedures is seen as a measure of improving the existing standards. In construction, QA is particularly important in improving the industry's image. The term QA can be interpreted in many ways and be applied to design, construction and operational use. The basic definition of QA is in BS 4778 and can be summarised as giving adequate confidence in the quality of goods or services (BS 4778).

The problem as far as the construction industry is concerned, is that BS 5750 (Parts 0 to 6) which outlines the quality system requirements on specification for design/development, production, installation and servicing, was written with manufacturing industry in mind, where product repetition is common and not for the construction industry where such repetitions are uncommon (BS 5750). This is further compounded by the fragmented nature of both design and the construction elements of the industry. Therefore the direct application of BS 5750 to the construction industry, requires careful consideration.

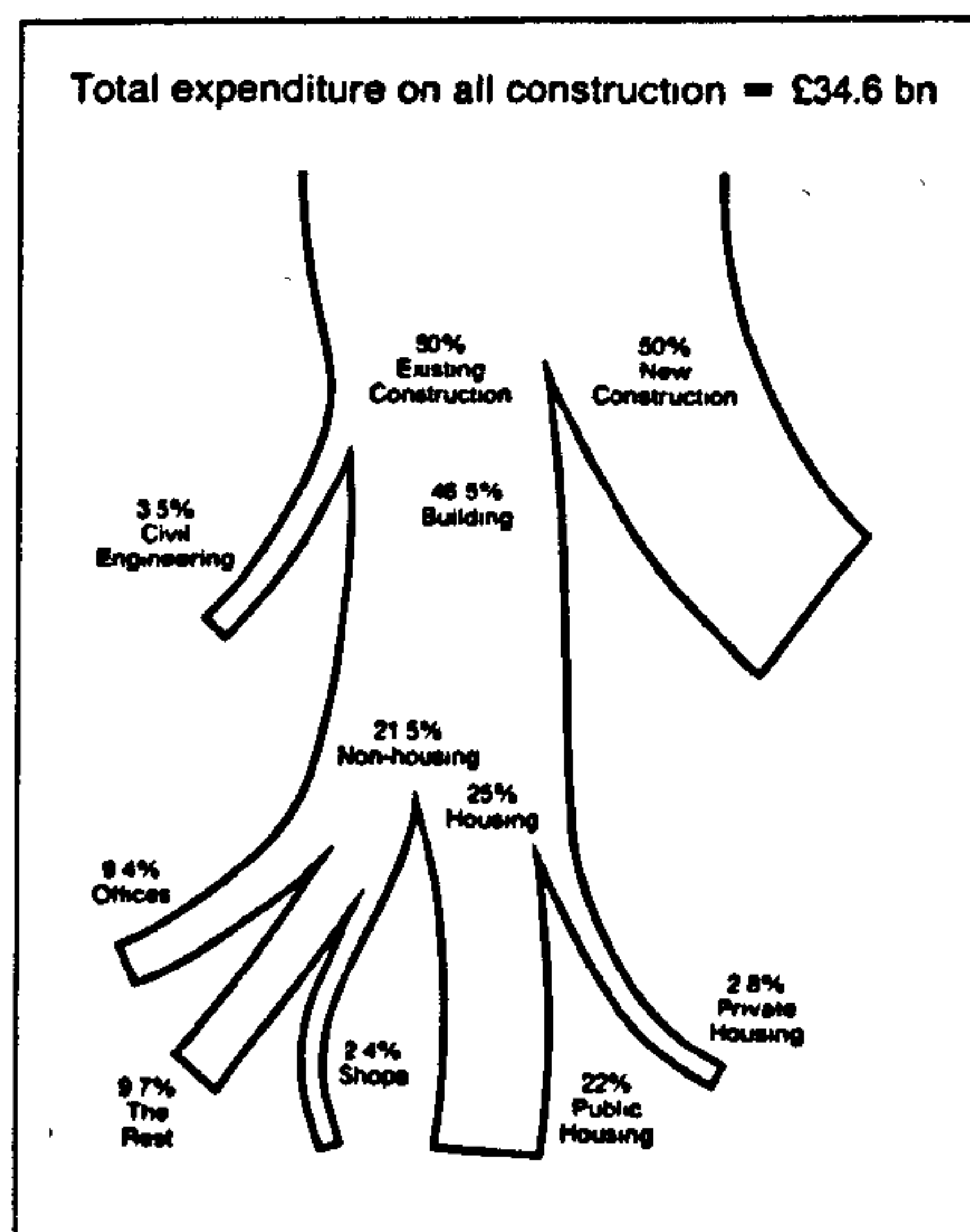
In general, QA is seen as an organisational structure of responsibilities, activities, resources and events that together provide procedures and methods of implementation to ensure the capability of an organisation to meet quality requirements. QA can therefore be interpreted as the verification of the actual performance of a building compared with the design intent. One way of achieving this is to monitor the performance of an existing building or component in practice, in order to establish whether the performance conforms with the required specification. This is seen as being central to decisions, relating to issues such as, upgrading the performance of the envelope and assembling evidence on whether some construction types have particular problems of QA.

In this context "QA is a formalised management system that provides 'conformance to requirements' consistently through regular audits" according to the Design Standards Office (DSO) of the Property Services Agency (PSA) [PSA - 1987].

A number of non-destructive testing procedures exist which can be viewed as appropriate QA methods for buildings. These include:

Thermographic inspection which can provide valuable data in identifying different classes of thermal abnormalities in the building envelope, such as local air-leakage, cold bridging effects and the correct installation of the insulation in the cavity walls and roof.

Specific measurements such as insitu tests may be carried out in order to monitor the performance of a building in service, by means of establishing the U values of walls, roofs or floors or pressure testing at junctions.



**Fig. 1.5:**

*Distribution of UK expenditure on repair and maintenance in 1987  
(After SERC Bulletin, Vol 4, No 5, Summer 1990)*



### **1.3 "U" value and its application in building design**

The separate processes of convection and radiation were investigated by Box in the context of heat transfer from a room to a the inner surface of the outer wall. A Table of wall overall transmission coefficients for the wall of a room when only one face is exposed "for outer walls of solid brick and stone construction" was first presented by Thomas Box in 1868. He described this quantity as "the value of U, or the loss in Units per square foot per hour", the symbol still used today for the wall transmission coefficient (Box - 1868).

The U value is a useful measure of the fabric performance and in particular of the overall insulating property of a construction, and is one of the most important properties of a component for energy conservation. Traditionally designers have relied on the simple steady state U value concept to assess the heat loss characteristics of the building fabric.

While different constructions may have the same U value their dynamic performance may be different. Although this is ignored by the U value concept it is nevertheless a quantity of considerable significance to both designers and regulators.

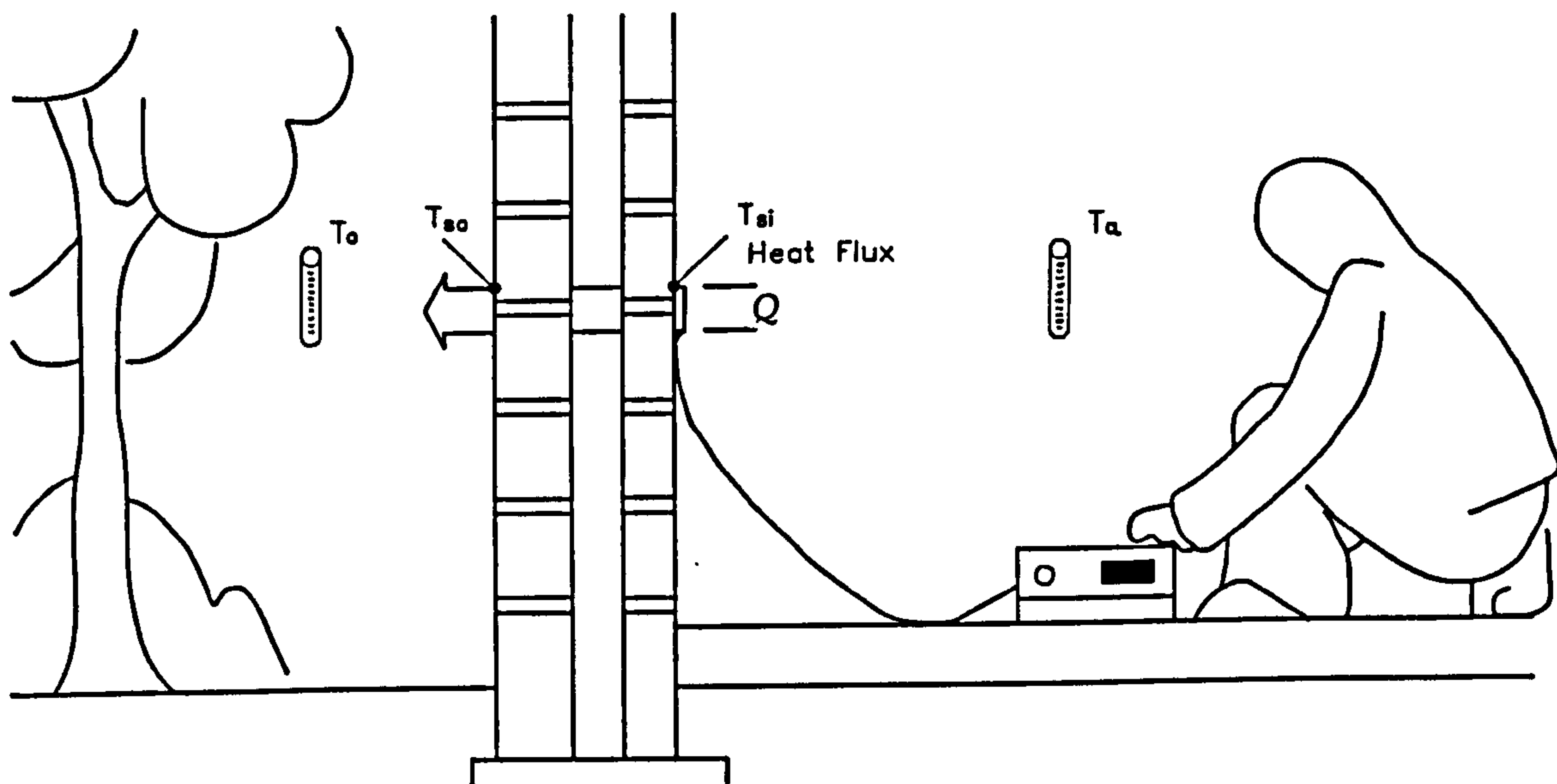
In order to emphasise the importance of U value as a useful guide for the estimation of plant loads or for comparison of insulation or establishing the thermal performance of the building, it may be useful to note that:

- (1) the U value concept includes assumptions and simplifications to meet practical needs
- (2) "design conditions" usually imply a unique temperature difference and steady state heat flow.

#### **U value and $\Lambda$ value**

The U value of a building element is a measure of the rate at which heat will flow through it per unit area under the influence of unit temperature difference and steady state boundary conditions. It is defined as the reciprocal of the total air-to-air resistance of unit area of the structure including the surface resistances.

If the resistances of the internal and external surface are omitted, then the reciprocal of the total surface-to-surface resistance of unit area of the structure is obtained and is called Thermal Conductance - the  $\Lambda$  value. The  $\Lambda$  value may be derived from simultaneous measurements of the heat flow rate ( $\text{W/m}^2$ ) through the wall, and of the internal/external surface temperature difference (deg. K) - (Fig. 1.6), using the relationship:  $\Lambda = Q/\Delta T$ .



**Fig. 1.6:**

**Measurement of heat flux through the building fabric**

*The heat flux  $Q$  is measured by the sensing head which is attached to the inner surface of the wall. The room is heated to an air temperature  $T_a$  which is higher than outside air temperature  $T_o$ . Inside and outside air or wall surface temperatures ( $T_{si}$  and  $T_{so}$  respectively) are measured simultaneously with the heat flux.*

*(Based on McIntyre -1985)*

$$U \text{ value} = \frac{\text{Average } (Q)}{\text{Average } (T_a - T_o)} \quad (\text{W/m}^2\text{K})$$

$$\Lambda \text{ value} = \frac{\text{Average } (Q)}{\text{Average } (T_{si} - T_{so})} \quad (\text{W/m}^2\text{K})$$

In this project, the  $\Lambda$  value is used for recovering and processing the data from field measurements, with measurements taking place across the wall surfaces and not from air to air.

#### **1.4 Measurements of the thermal performance of the building fabric**

The rationale underlying the insitu measurement of a wall's thermal transmittance is that the measured value is a valid indicator of the wall's performance and can be legitimately compared with the theoretical or expected performance.

The measured value is the best estimate of the insitu performance and the theoretical value is the best estimate of how the wall component is expected to perform. Each estimate is accompanied by uncertainty and consequently so is the comparison. For example:

How accurately can the wall's thermal transmittance be calculated?

What are the dimensions and thermal properties of the wall?

What is the thermal resistance of the cavity?

What is an appropriate theoretical model for calculating transmittance - one, two or three dimensional heat flow?

How accurately can the wall's thermal transmittance be measured?

What are the errors involved in the field measurements?

How can a steady state value of thermal transmittance be derived from dynamic data?

Is the measured value representative of the average performance of the wall?

These and other relevant issues are examined in this thesis in order to provide an estimate of the uncertainties involved.

The study is concerned with obtaining reliable measures of the steady-state  $\Lambda$  value of constructions from field measurements where the constructions are subjected to transient boundary conditions. This area is relatively well developed with both the conditions of measurement and the analysis techniques having been addressed in some depth (e.g.



Flanders and Marshall - 1982, Siviour and McIntyre - 1982, Roulet et al - 1985, Anderson - 1985, McIntyre - 1985, Isaacs and Trethowen - 1985).

The experimental evidence which has been accumulated sometimes indicates good correspondence between measured and predicted values (Anderson and Ward - 1981, Brown and Schuyler - 1982, Wavre - 1984, Roulet et al - 1985) but in others (Flanders and Marshall - 1982, Siviour 1982) this has not been the case with the insitu measured value being considerably different from the expected value. These departures from expected values have not been adequately explained, but may be in part due to:

- errors in the measurement technique employed
- the quality of workmanship
- variable material properties
- moisture content
- the presence of mortar joints and ties
- assumptions made in the calculation method

A further feature of these studies is that they are often concerned with "one off" examples measured at one point in time. There is little information on the variability to be expected from a given form of construction or its seasonal performance.

Evidence on the variability to be expected due to materials/tolerances/workmanship involved in a given construction are relatively unknown. For example, Roulet et al's (1985) measurements indicate that there is a 20% variation in thermal transmittance due to local variations in a homogeneous concrete wall, whilst Anderson and Ward (1981) observed less than a 5% variation in the measured thermal resistance of an insulated ceiling.

The measured  $\Lambda$  value may also experience large variations due to the changing moisture content of the materials making up the wall. Fitt and Day (1984) have calculated that evaporative effects, let alone the changing thermal conductivity of the material, can increase the heat transmission through the wall and hence its apparent U value by 10% over a heating season. Higher values may be expected during wet periods, typically of the order of 30% according to Bogle et al (1984).

Air movement through the structure might also be expected to affect performance, although no data is available as to the extent of any variation that this may introduce (Dickson - 1981, Bankvall - 1982).

In practice, therefore, a unique value for the thermal transmittance of a wall must not be expected for a given construction, but rather a distribution of values which will be dependent upon the variabilities introduced into its design, construction and use.



## **Objectives**

The main objective of the study is to provide information on the in-service performance of constructions and the extent to which the widely accepted prediction techniques accurately reflect the actual behaviour of the component. It may be broken down into the following research objectives:

- (1) To establish the uncertainty introduced by the measurement and analysis techniques adopted.
- (2) To measure the insitu thermal transmittance of a range of wall constructions representative of both the existing building stock and new build.
- (3) To provide an estimate of the inherent variability in the performance of the wall construction due to factors such as workmanship.
- (4) To compare the measured and predicted values for the wall constructions, in order to assess the walls performance in practice.

Chapter 2 presents a brief account of the heat transfer mechanisms taking place in wall constructions and a review of thermal modelling techniques.

Chapter 3 addresses field measurements in general; a review of potential insitu measurement techniques and a description of the actual equipment and conditions applied to the field measurements undertaken in this study.

Chapter 4 reviews appropriate theoretical models used to calculate the heat flow through a wall construction and outlines the uncertainties involved in the calculation.

Chapter 5 focuses on the uncertainties involved in field measurements. The emphasis is on issues that can influence the final  $\Lambda$  value such as, the calibration of the measuring sensors, the attachment of the measuring sensors on the wall surface, the boundary conditions in the enclosure at the time of the measurement and the length of the monitoring period.

Chapter 6 considers the results of the field measurements on 4 generic wall types undertaken in the Newcastle area and compares the measured with the theoretical values.

Chapter 7 is concerned with the conclusions of this thesis and the areas for further work.

**HEAT TRANSFER PROCESSES  
IN  
OPAQUE BUILDING ELEMENTS**

**CHAPTER 2**

## **2.0 Introduction**

Heat flow is energy in transition under the influence of a temperature difference. The study of heat transfer deals with the mechanism by which such energy is transferred and the rate at which the exchange will take place under certain specified conditions.

A short review is offered and primary attention is directed towards the conditions under which, measurements are carried out in the field, the physical processes involved, and the models used to represent them, all in the context of heat flow through the external wall envelope.

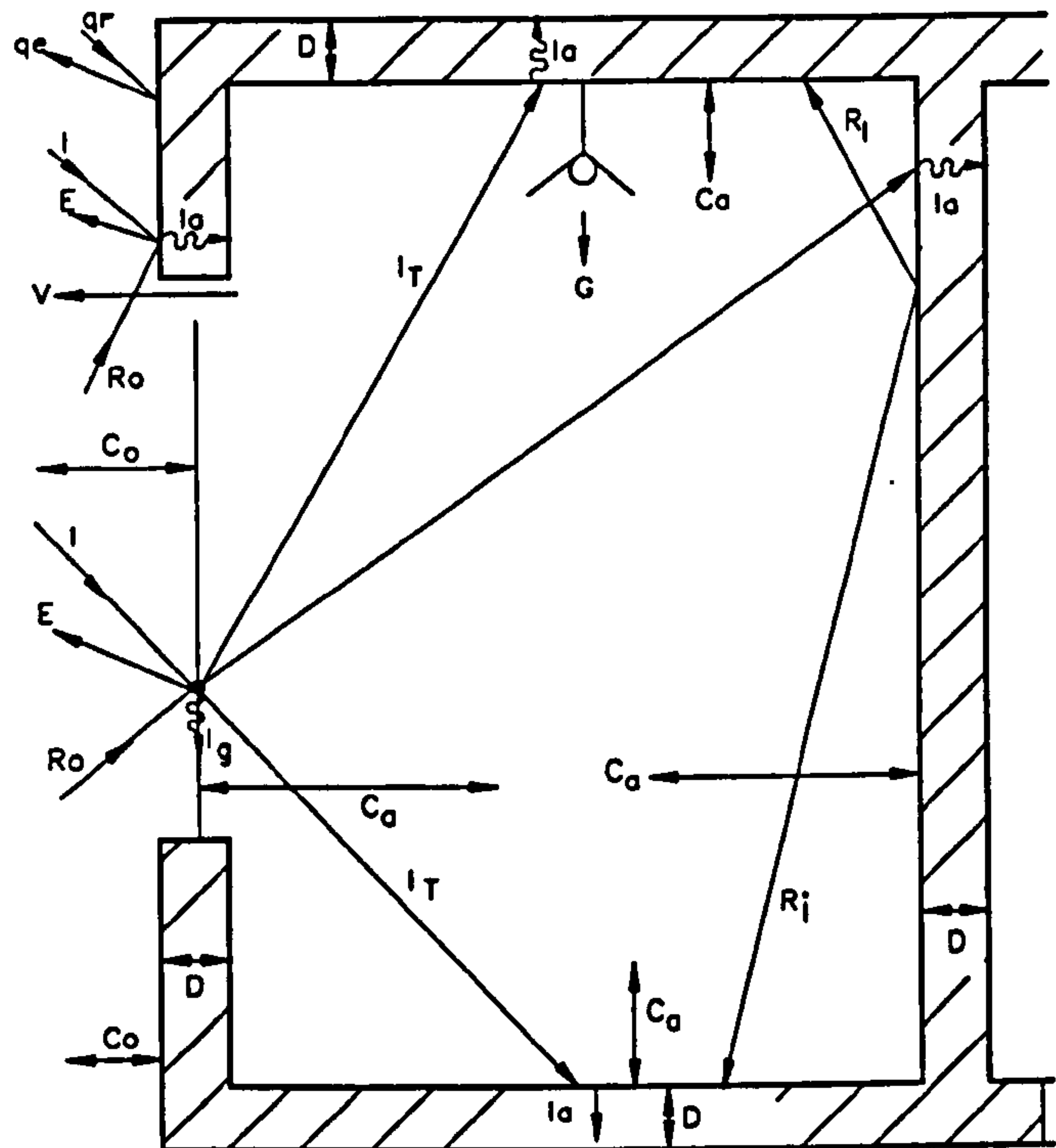
### **2.1 Thermal processes in an enclosure**

Any building element may be considered as being part of a system, and at any time is subjected to complex heat flow processes under dynamic conditions. In the context of the present study, the external wall forms part of a system which is part of the enclosure illustrated in Fig. 2.1. In order to establish the thermal transmittance value of an external wall, the thermal processes taking place in that wall - mainly conduction through the wall fabric (D) - must be viewed in the context of the processes taking place in both the internal and external environment of the enclosure.

However, for the conduction process to be seen in context first an understanding of the energy exchanges taking place within, and at the surfaces of, building components is required. These energy exchanges may be divided into three groups:

- (1) the internal energy exchanges resulting from the conductive and heat storage processes occurring within the body of the building component.
- (2) the internal surface energy exchanges resulting from the longwave and shortwave radiative and convective heat flows between the internal surface and the room enclosure.
- (3) the external surface energy exchanges resulting from solar and longwave radiative exchanges and the convective heat flow between the external surface and the environment.

Firstly, the conduction process through the wall fabric is looked at, followed by an examination of the convective and radiative exchanges at the wall surfaces.



where

- $I$  = External incident solar radiation (direct + diffuse)
- $I_a$  = Fabric absorbed solar radiation (direct + diffuse)
- $I_g$  = Glazing absorbed solar radiation (direct + diffuse)
- $I_T$  = Attenuated solar radiation (direct + diffuse)
- $E$  = Radiation emitted from surface
- $R_o$  = Longwave radiation from atmosphere and ground
- $R_i$  = Longwave radiation between all internal surfaces
- $C_o$  = Convective exchange with ambient air
- $C_a$  = Convective exchange with inside air
- $D$  = Conduction through fabric
- $G$  = Convective and radiative heat gains from all sources (heat emitters, people, lights)
- $V$  = Ventilation exchange
- $q_r$  = Direct chilling due to rainfall
- $q_e$  = Evaporative heat flux away from wall

**Fig. 2.1:**  
*Simultaneous thermal processes taking place in a room which affects the heat flow through the external wall*



## 2.2 Heat conduction through the building envelope

Heat is transferred through the building envelope primarily by conduction. When voids or cavities are within the envelope, two other mechanisms may be involved: natural convection and radiation. Firstly the case of transient conduction will be examined.

Transient heat conduction is characterized by time-dependent heat flow and temperature pattern within the conducting body. The general differential three dimensional (3D) heat conduction equation (for constant thermal conductivity), is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{\lambda} = \frac{1}{\alpha_d} * \frac{\partial T}{\partial t} \quad (2.1)$$

where

$T$  = Temperature ( $^{\circ}\text{C}$ )

$\dot{q}$  = rate at which energy is generated per unit volume ( $\text{W}/\text{m}^3$ )

$\lambda$  = Thermal conductivity ( $\text{W}/\text{mK}$ )

$t$  = Time (s)

$\alpha_d$  = Thermal difussivity ( $\text{m}^2/\text{s}$ )

$= \lambda/\rho c_p$  where  $\rho$  = density ( $\text{Kg}/\text{m}^3$ ) and  
 $c_p$  = specific heat ( $\text{J}/\text{KgK}$ )

Three dimensional transient conduction exists in real problems. However, a great number of problems of practical engineering interest may be approximated rather well by making the assumption of one dimensional (1D) conduction. That is, a plane wall of finite thickness but infinite in extent in all other directions so that the conduction may be taken as one dimensional.

$$Q = -\lambda A \frac{dT}{dx} \quad (\text{W}) \quad [\text{heat rate by conduction}] \quad (2.2)$$

where  $A$  is the surface area ( $\text{m}^2$ )

The simplification of the 3D conduction problem to 1D involves the following assumptions:

- (1) Edge effects in a wall resulting from windows, corners and edges are sufficiently small as to be ignored.
- (2) The wall has a constant conductivity (homogeneous throughout).
- (3) The temperature field on each face of the wall is spatially uniform.

It should be noted that (1) and (2) are essentially a function of the geometry and the construction of the wall and (3) is a function of the geometry and the boundary conditions which are examined in more detail in a later section. Consequently, it is unlikely that the above conditions can be fully met in a "real" wall.

Buildings are subject to a variety of influences affecting the wall heat flow:

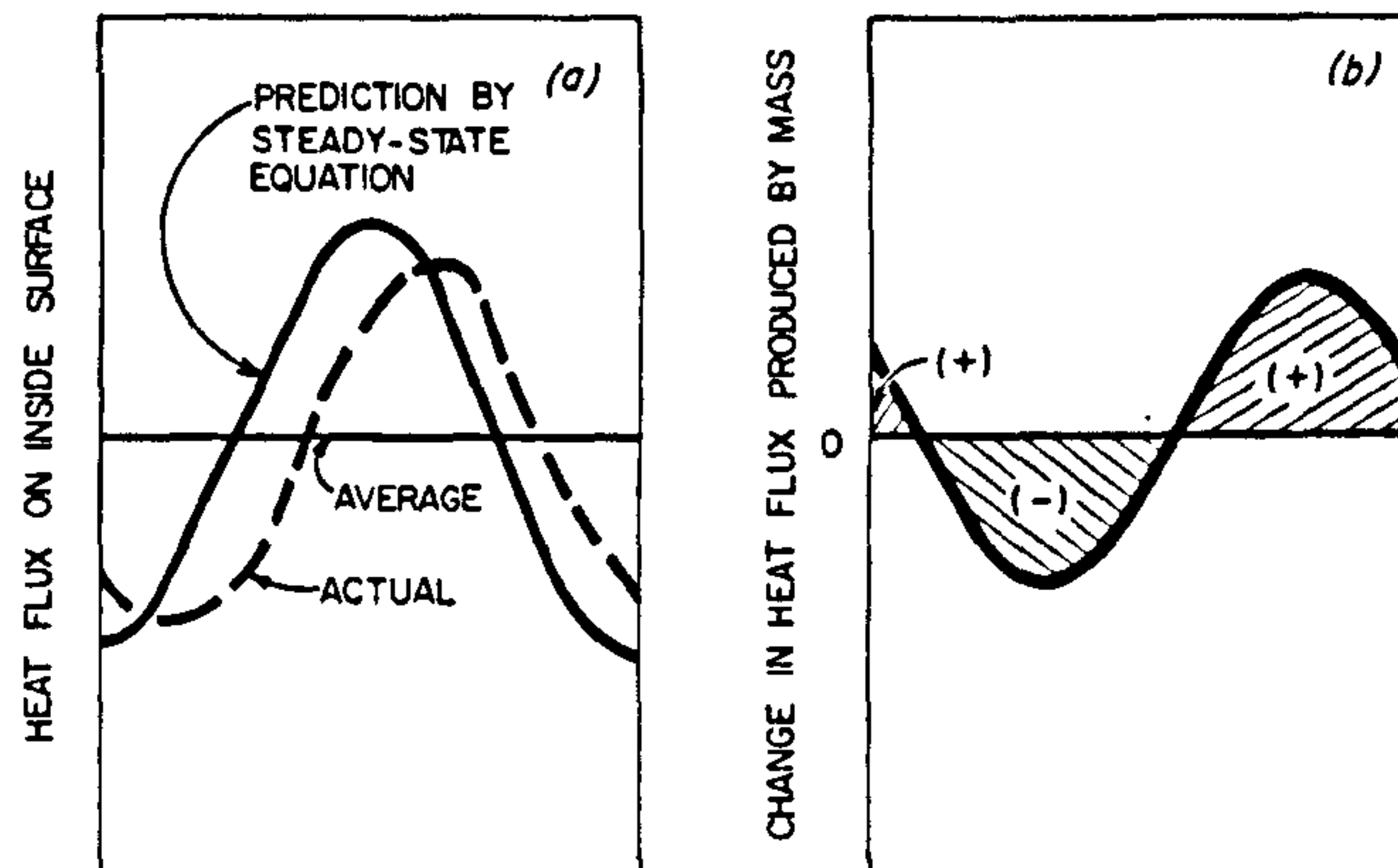
- (1) continuous variation in external air temperatures and wind
- (2) variation in the intensity of solar gains
- (3) internal heat gains from people, artificial lighting, equipment, etc.,  
the extent of which is often unpredictable.

The way in which the building fabric as a whole responds to these changes has a considerable effect on the thermal conditions inside the building and the energy stored within its fabric.

Of particular importance is the rate at which the internal surface temperature is likely to fluctuate during any 24 hour period. Assessment of likely fluctuations requires consideration of both heating up and cooling down of the fabric. There is a difference in response between thermally heavyweight and lightweight constructions. The thermal storage in the fabric plays an important role in the dynamic behaviour of the wall envelope and the thermal response is associated with the thermal performance of the building as a whole over a period of time to changing heat inputs. A significant amount of work has been carried out in characterising the dynamic thermal behaviour of the wall (Mitalas and Stephenson - 1967, Milbank and Harrington Lynn - 1974, Ahvenainen et al - 1980, Anderson - 1985).

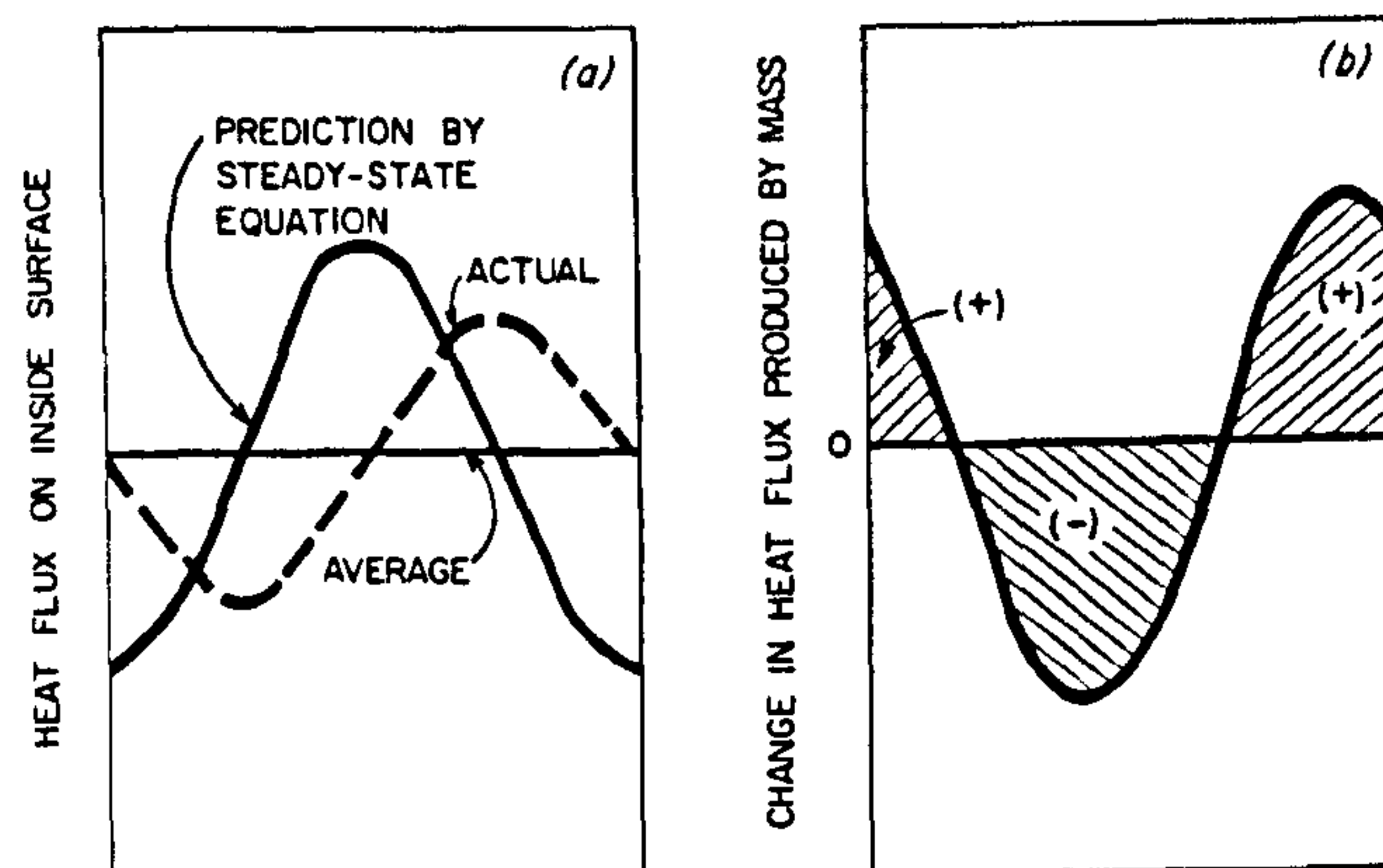
Mass has two effects on the energy flows in the building fabric. The first of these is to produce a time lag and amplitude reduction in the heat flux at the inside surface of the envelope resulting from variations in the boundary conditions. The second effect is the ability of the wall fabric to store energy, and, subsequently, release it to the air, that is, if it is not isolated from the air by insulation.

Fig. 2.2 indicates the idealised behaviour of homogeneous walls exposed to a 24 hour, sinusoidal temperature variation on the outside and a fixed temperature on the inside. The behaviour of non-homogeneous walls is similar. In part (a) of each Figure, the actual heat flux for an entire cycle is plotted along with the heat flux calculated by assuming that steady-state conditions always exist. In part (b), the change in heat flux resulting from the mass is plotted. This change is just the difference between the actual and steady-state values. It should be noted that the average heat flux is not influenced by the mass (Childs et al - 1983).



**Fig. 2.2 (i):**

*Heat flux on inside surface of a homogeneous wall, 3-h lag*



**Fig. 2.2 (ii):**

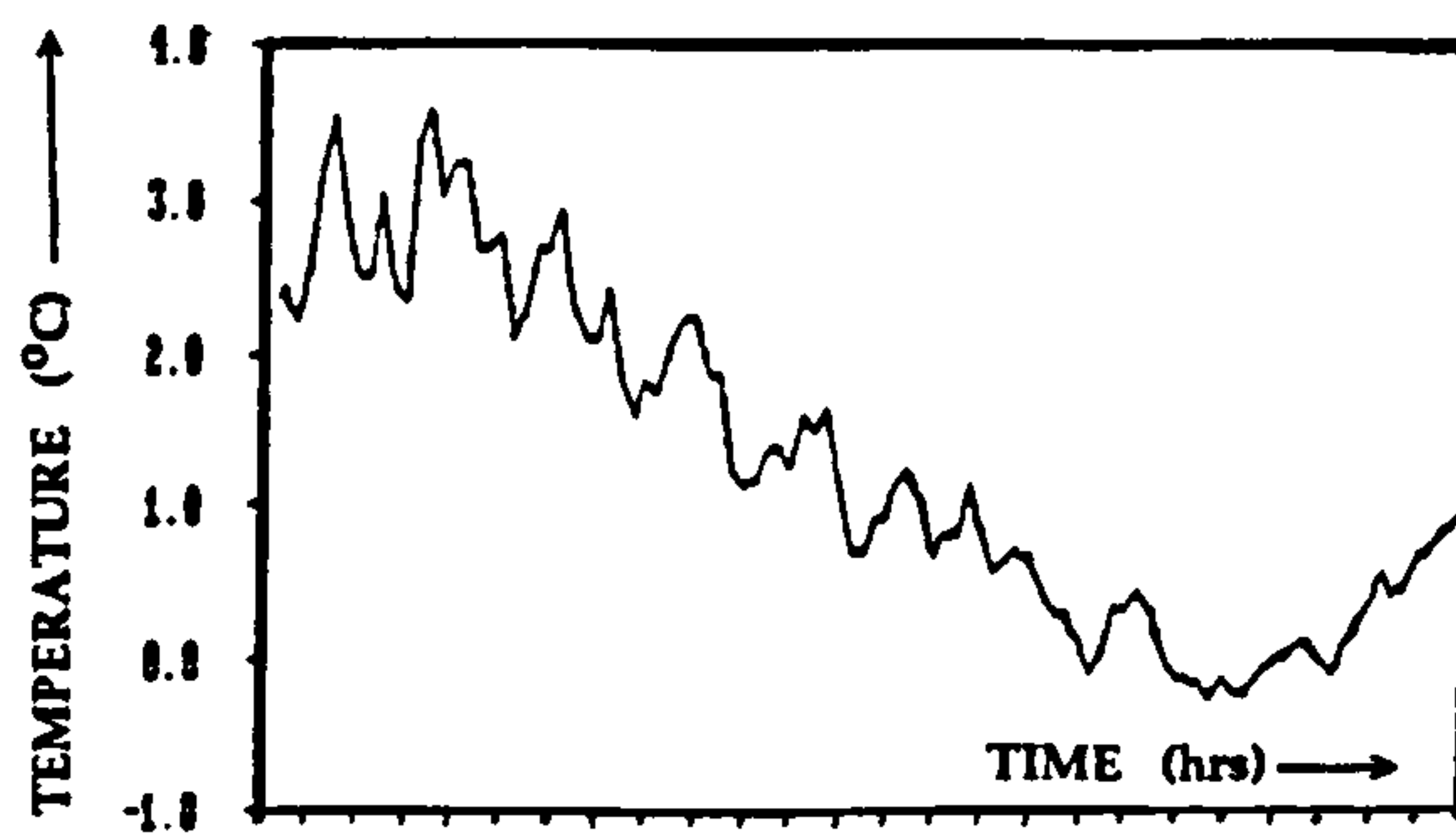
*Heat flux on inside surface of a homogeneous wall, 6-h lag*

**Fig. 2.2:**

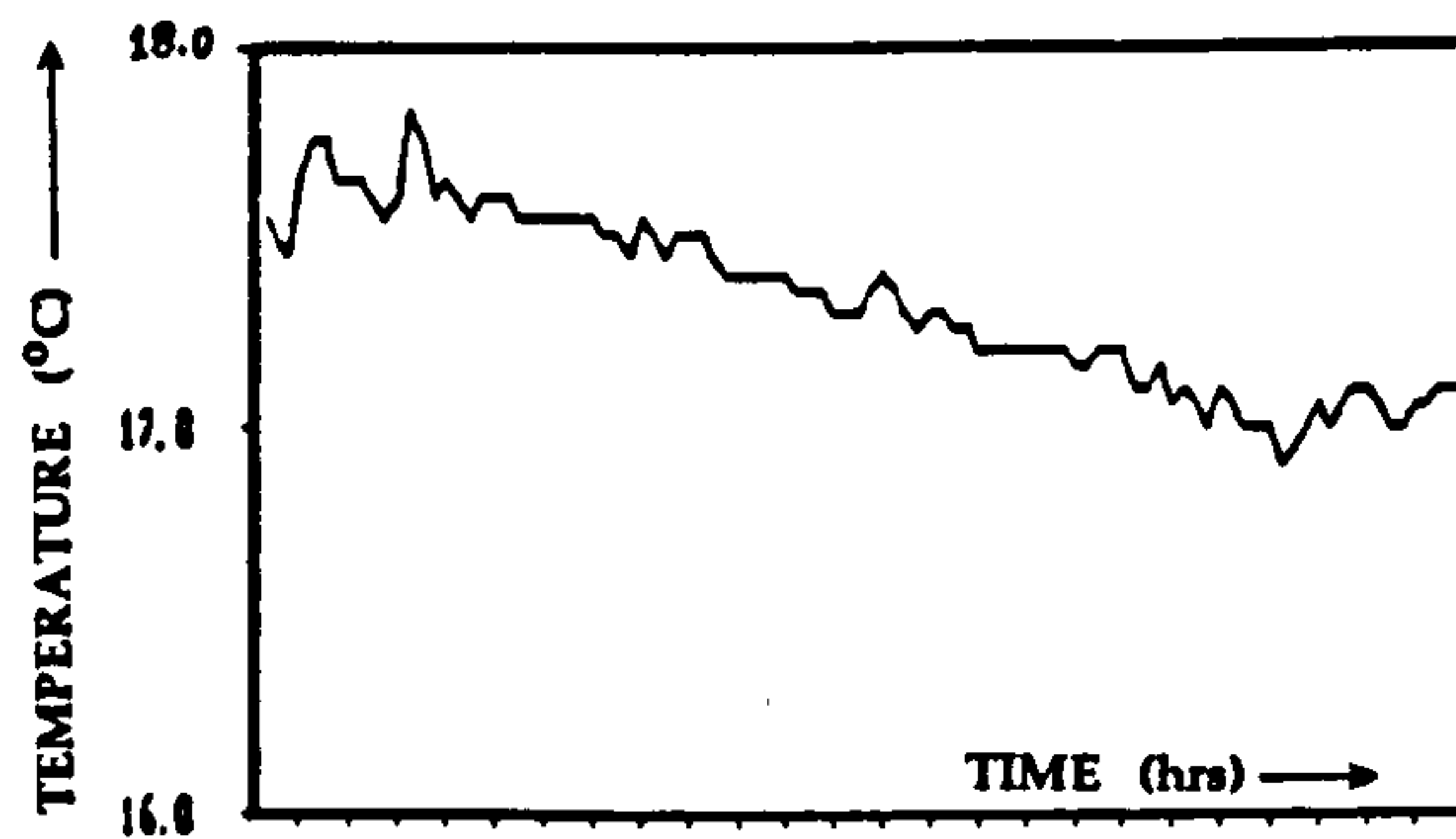
**Idealised heat flow pattern**

*(After Childs et al - 1983)*

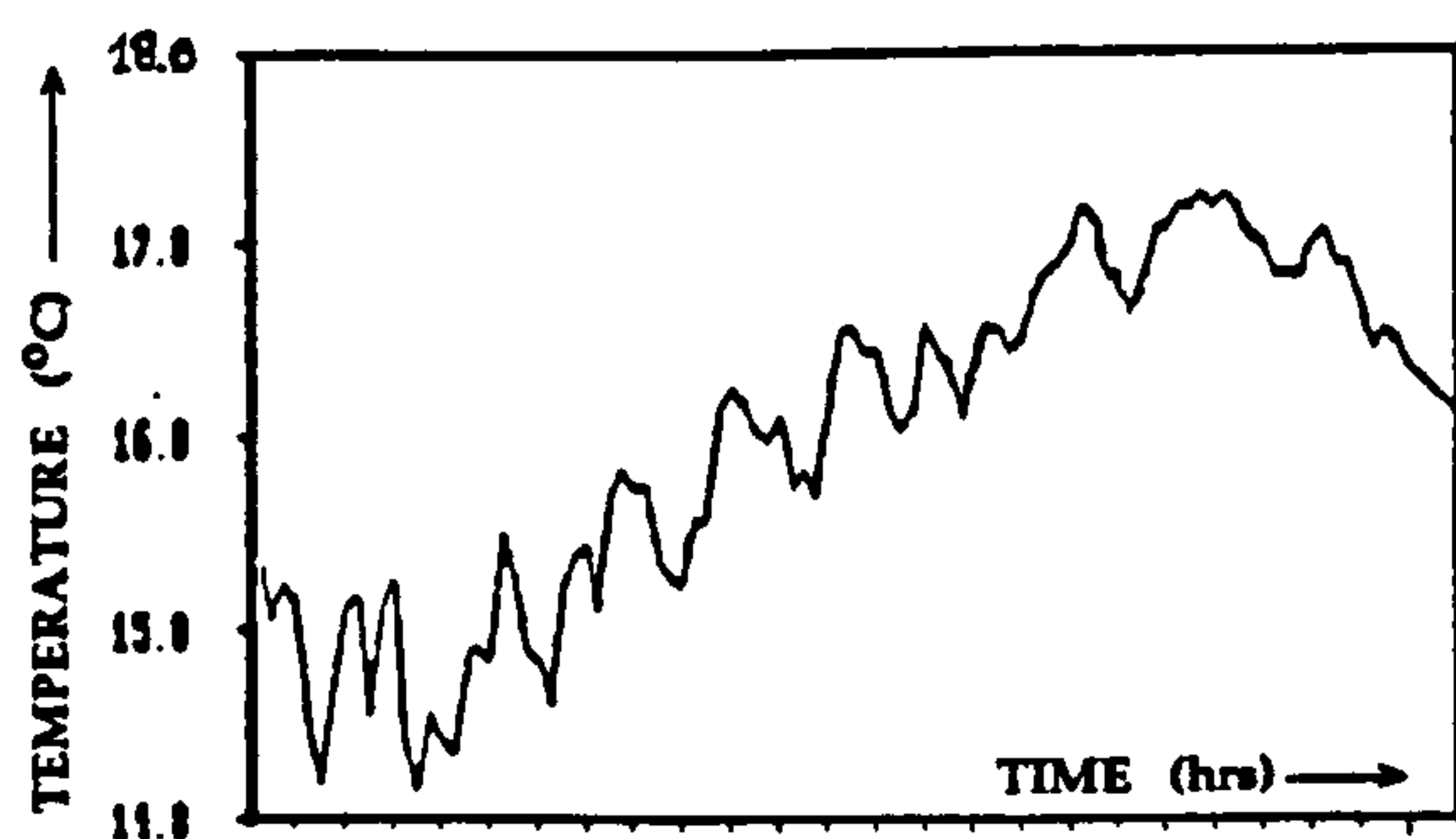




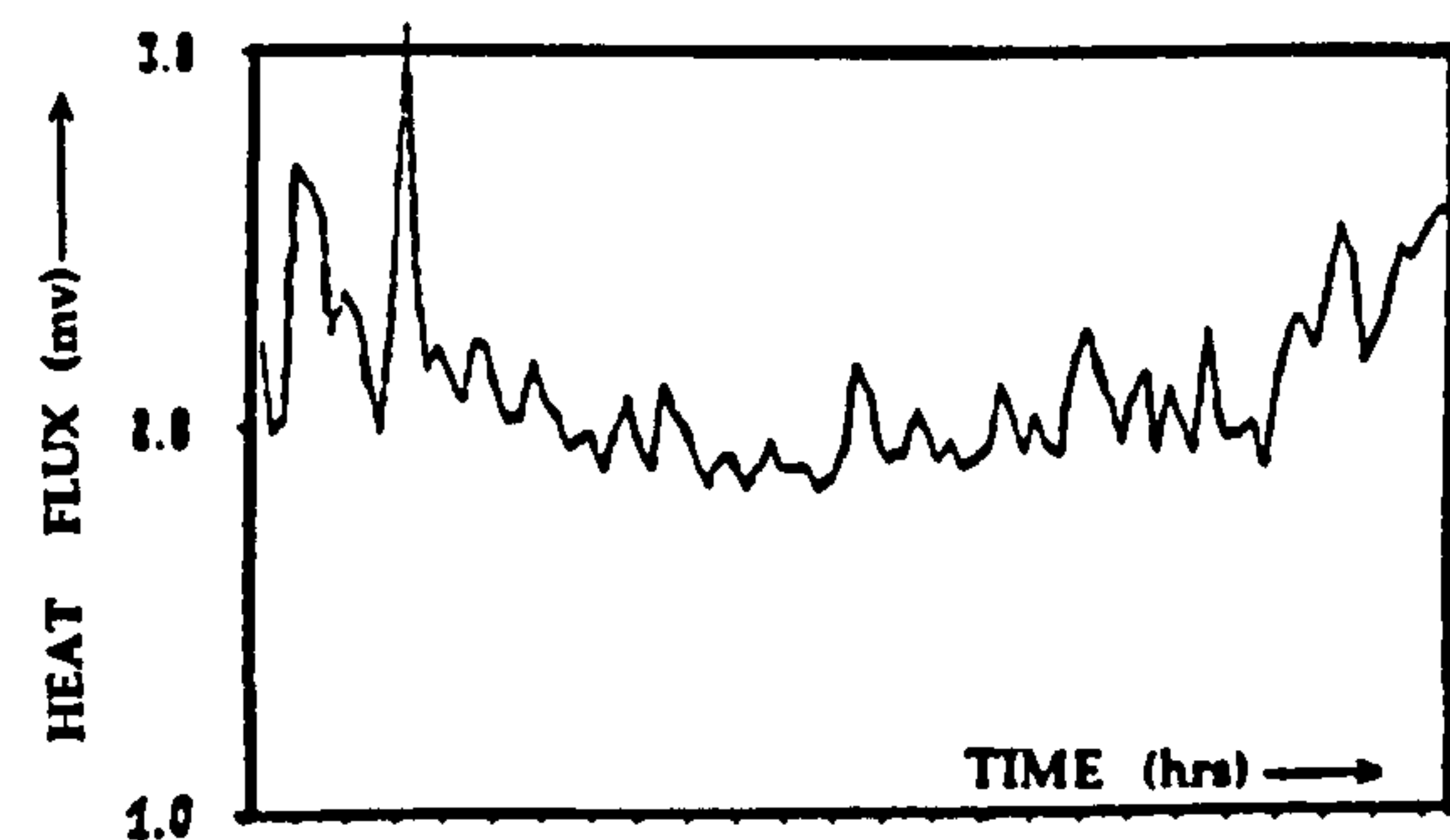
(i) Temperature at the external surface of the wall



(ii) Temperature at the internal surface of the wall



(iii) Temperature difference between wall surfaces



(iv) Heat flux measured at the internal wall surface

Fig. 2.3:

Dynamic heat flow pattern through the wall fabric over a 24hr period

(Data taken from present study - chapter 6)

However, in practice the inputs are not sinusoidal and are not restricted to external variations. In addition, short term transients of minutes or seconds, due to light switching, etc., will change the driving forces on the wall which leads to complicated dynamic heat flow patterns (Fig. 2.3).

The response to this complicated problem involves two fundamentally different approaches:

- (1) to model in greater detail, the transient heat flows by means of thermal modelling techniques (see section 2.6 of this chapter).
- (2) to use average boundary conditions such that the short term thermal behaviour of the wall is averaged out, i.e. to give steady state conditions.

The latter approach is the one which is mostly used to try and recover values from measurements under dynamic conditions (Flanders and Marshall - 1982, McIntyre - 1985, Issacs and Trethowen - 1985).

## **2.3 Boundary conditions**

Boundary conditions at the internal and external surfaces of a building are complex and they include: convection and longwave radiation. They have been shown to be highly unstable varying in both time and space over the wall surface. Shortwave (solar) radiation must also be taken into consideration. A brief account of the appropriate theory is given below.

### **2.3.1 Convection**

When a fluid flows over a solid surface at a different temperature, heat is transferred between them by the combined effects of convection and conduction. This process is called convective heat transfer. Convective heat transfer is assisted by mixing motion of the fluid. If the mixing is due to natural buoyancy forces resulting from density changes it is called "natural" or "free" convection whereas if it is due to artificially produced forces such as with a pump or fan it is called "forced".

Convection is far more difficult to analyse than conduction because it is a combined problem of heat flow and fluid flow. The rate of heat transfer is influenced by all the fluid properties that can affect both heat and fluid flow, such as velocity, thermal conductivity, viscosity, density, thermal expansion, etc. The differential equations describing fluid dynamics of convective heat transfer belong to one of the most difficult classes in theoretical physics.

The basic relationship for heat transfer  $Q$  between a fluid and its boundary of area  $A$  was first given by Newton in 1701 as

$$Q \propto A * \Delta T$$

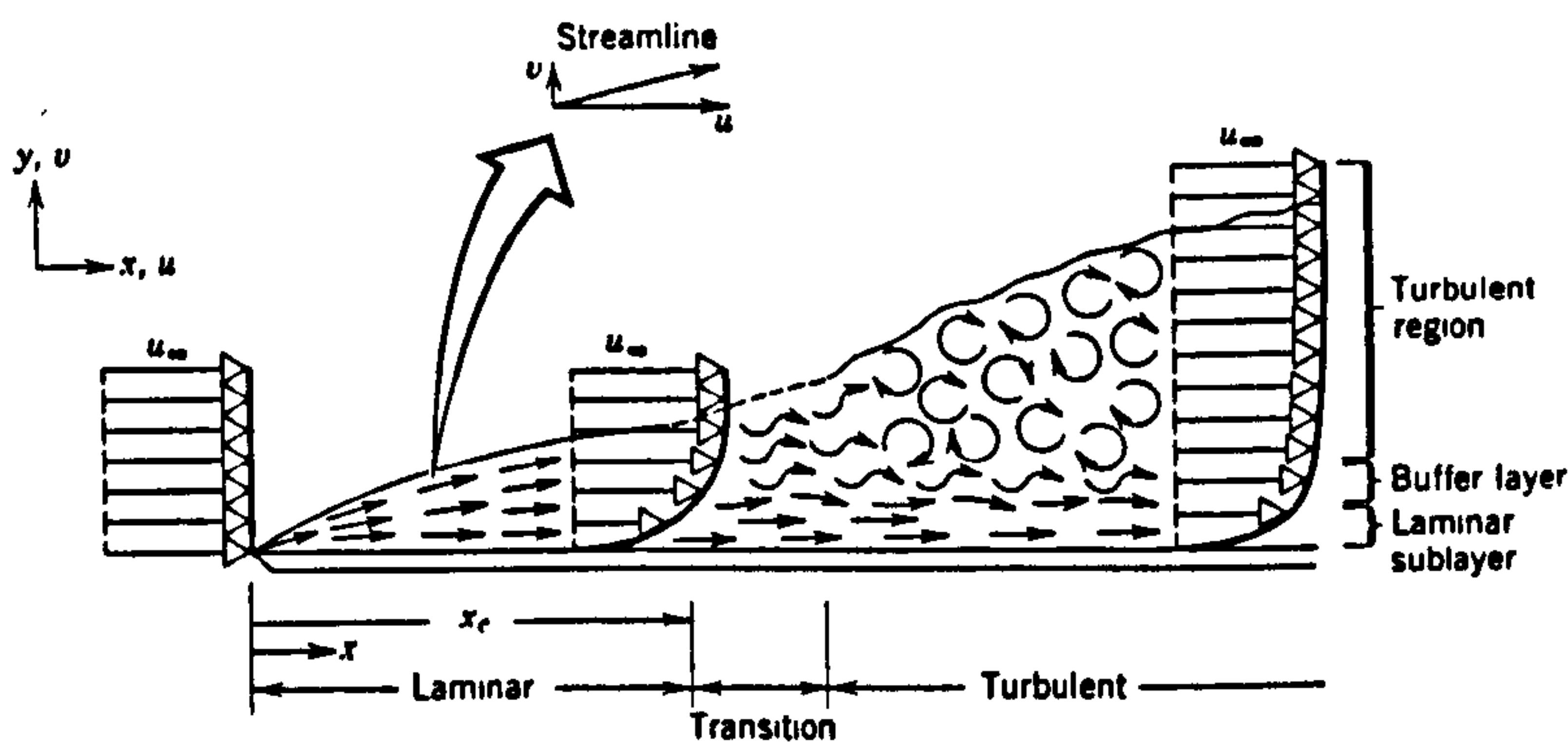
where  $\Delta T$  is the temperature difference between the fluid and the boundary surface.

Introducing a constant of proportionality  $h_c$  which is designated as the surface heat transfer coefficient, gives:

$$Q = h_c * A * \Delta T \quad (2.3)$$

### Boundary layer theory

For the flow over a flat plate as shown in Fig. 2.4 a region starts to develop at the beginning of the leading edge of the plate, where the influence of viscous forces is felt. The boundary layer is the region of flow which develops from the leading edge of the plate in which the effects of viscosity are observed. The boundary layer ends at the position which is specified by some arbitrary point. This point is usually chosen as the coordinate where the velocity becomes 99% of the free-stream value. Initially the velocity at the wall is zero and increases from this value to the free stream value at some distance from the wall. The distance is termed the boundary layer thickness and can be seen to increase in thickness along the plate.



**Fig. 2.4:**

*Velocity boundary layer development on a flat plate  
(After Incropera and DeWitt - 1985)*



Initially, the boundary layer starts to develop in a "laminar" manner, but at some critical distance from the leading edge, depending on the flow field and flow properties, small disturbances in the flow begin to amplify, and a transition process takes place until the flow becomes turbulent. A rapid increase in the friction is produced by the transition from laminar to turbulent flow as the turbulent motion dissipates the energy. For a more detailed study of the boundary layer theory, reference should be made to Sturrock (1971).

The transition is characterized by the Reynolds number which relates the free stream velocity and fluid properties, to a characteristic length where the transition occurs. Although the critical Reynolds number for transition on a flat plate is usually taken as  $5 \times 10^5$  for most analytical purposes, the critical value in a practical situation is strongly dependent on the surface-roughness conditions and the "turbulence level" of the free stream.

The relative shapes for the velocity profiles in laminar and turbulent flow are indicated in Fig. 2.4. The laminar profile is approximately parabolic, while the turbulent profile is very nearly linear. This linear portion is said to be due to a laminar sublayer which is situated very closely to the surface. Outside this sublayer the velocity profile is relatively flat in comparison with the laminar profile.

### Dimensional analysis

Current building design practice uses values of convection coefficient based upon dimensional analysis. The concept of dimensional analysis rests on the well known rule that any mathematical expression correctly relating physical quantities must be dimensionally homogeneous i.e. both sides of the equation must have the same dimensions. It can be shown through dimensional analysis that a functional relationship (Rogers and Mayhew - 1980) exists such that,

$$Nu = f(Pr, Gr, Re)$$

where

Nu is the Nusselt number

Pr is the Prandtl number

Gr is the Grashoff number

Re is the Reynolds number

$$Nu = h_c x / \lambda$$

$$Pr = C_p \mu / \lambda$$

$$Gr = \rho^2 x^3 \beta g \Delta T / \mu^2$$

$$Re = \rho v x / \mu$$

where

$x$	is a characteristic dimension (m)
$\lambda$	is the fluid thermal conductivity (W/mK)
$C_p$	is the specific heat at constant pressure (J/KgK)
$\mu$	is the fluid dynamic viscosity (Kg/ms)
$\rho$	is the fluid density (Kg/m <sup>3</sup> )
$\beta$	is the coefficient of expansion (K)
$g$	is the gravitational constant (9.81 m/s )
$\Delta T$	is the difference between the surface and the bulk fluid temperature (K)
$u$	is the fluid velocity (m/s)

### Natural convection

The first three dimensionless groupings are of importance in natural convection estimation, since there is no forced velocity and the Reynolds number disappears from the equation.

Therefore  $Nu = f(Gr, Pr)$

The functional relationship is given by:

$$Nu = c (Gr)^x * (Pr)^y$$

The values of the constants  $x$  and  $y$  are published in a number of textbooks (Chapman - 1984, Incropera and DeWitt - 1985). Since natural convection is dependent upon the orientation of the surface, values are generally quoted for both vertical and horizontal surfaces.

The evaluation of the natural convection heat transfer is mainly experimental, i.e. heated plates under experimental conditions. This is the way that most data correlations have been obtained. There is a rich body of literature on the subject, for example: Jacob (1949), Fishenden and Saunders (1950), McAdams (1954), Min et al (1956), Fujii and Imura (1970), Wong (1977), Alamdari and Hammond (1983), [see also Figs. 2.5 and 2.6].

## **Forced convection**

When considering forced convection, the gravitational effects are generally negligible in comparison with the forced velocity. It is possible to ignore the Grashoff number in the general equation.

Therefore 
$$\text{Nu} = f(\text{Re}, \text{Pr})$$

The functional relationship is given by:

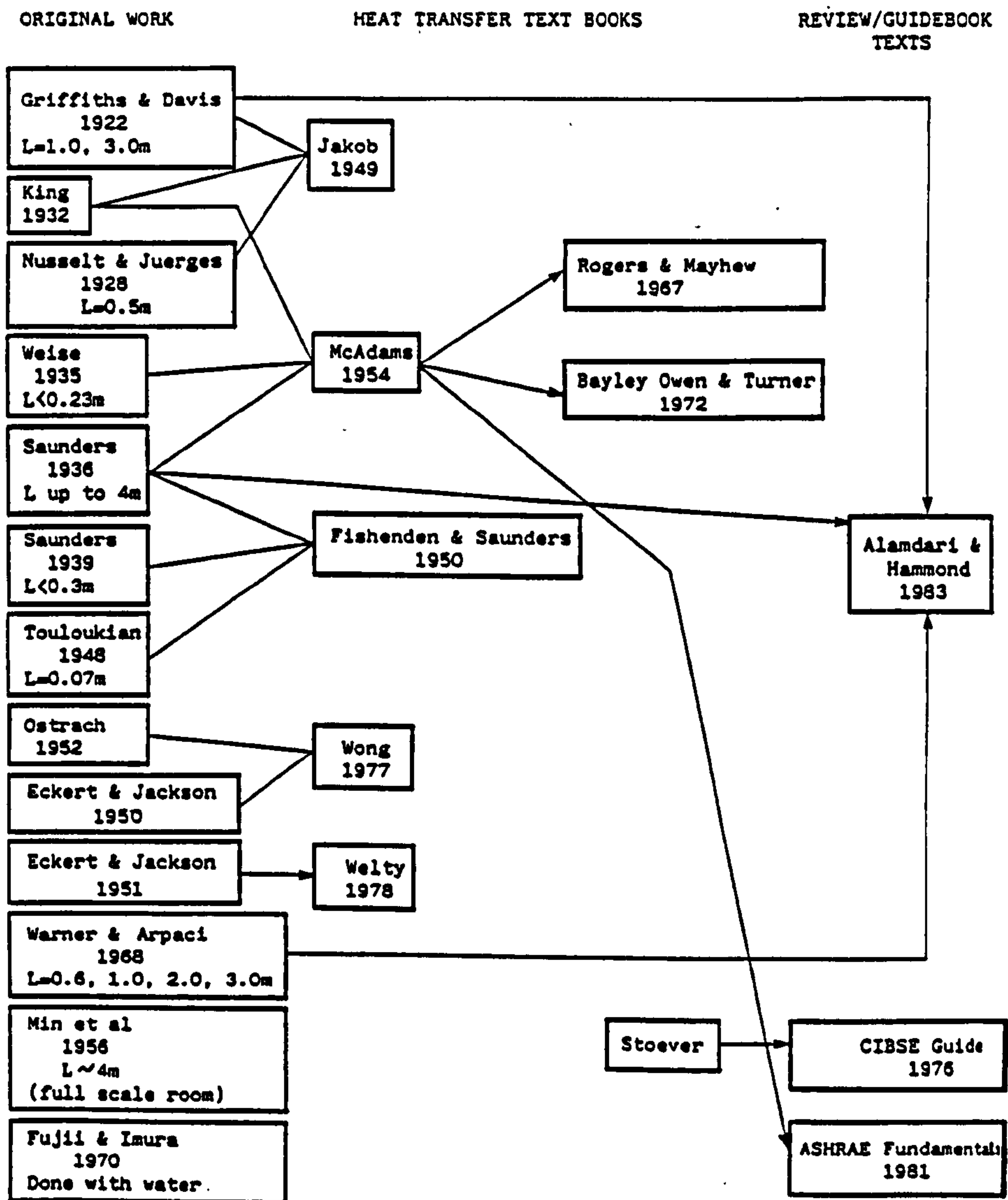
$$\text{Nu} = c (\text{Re})^n * (\text{Pr})^m$$

where  $c$ ,  $n$  and  $m$  may be assessed from experimental observation or theoretical considerations or may be found in the existing literature (Chapman - 1984, Incropera and DeWitt - 1985).

Values for forced convection are generally obtained from direct relationships between the convection coefficient and air speed. Such relationships have been obtained experimentally from both wind tunnel measurements (during the period 1920 - 1970) and, more recently, by field measurements.

Field measurements as applied to the external surface of a building were carried out by Sturrock (1971), Ito et al. (1972), Sharples (1981, 1984) who comment on the validity of previous established relationships adopted by ASHRAE and the CIBSE Guide.





**Fig. 2.5:**  
*Sources of surface convective heat transfer correlations for VERTICAL surfaces*  
*(After Halcrow - 1987)*

Heat Transfer Text/Paper	VERTICAL SURFACE	
	Laminar ( $Gr < 10^9$ )	Turbulent ( $Gr > 10^9$ )
Jacob (1949) Text book	$Nu = 0.509 Gr^{1/4}$ (data from Nusselet and Juerges, 1928 and King, 1932)	$Nu = 0.115 Gr^{1/3}$
Fishenden and Saunders (1950) Text book	$Nu = 0.514 Gr^{1/4}$ (data from Saunders, 1936, Saunders 1939 and Touloukian 1948)	$Nu = 0.107 Gr^{1/3}$
McAdams (1954)  Text book	$Nu = 0.505 Gr^{1/4}$ (data from King, 1932) $Nu = 0.541 Gr^{1/4}$ (data from Weise, 1935 and Saunders, 1936)	$Nu = 0.116 Gr^{1/3}$ (data from King, 1932, and Saunders, 1936)
Min et al (1956) Original paper		$Nu = 0.197 Gr^{0.32}$
Rogers & Mayhew (1967)  Text book	$Nu = 0.504 Gr^{1/4}$ (theoretical solution) $h_c = 1.42 \left(\frac{\Delta T}{L}\right)^{1/4}$ From McAdams, 1954	$h_c = 1.31 (\Delta T)^{1/3}$
Fujii and Imura (1970) Original paper	$Nu = 0.514 Gr^{1/4}$	
Bayley, Owen & Turner (1972) Text book	Use McAdams, 1954	
CIBB Guide (1976)	$Nu = 0.48 Gr^{1/4}$ (from Stoever)	$Nu = 0.119 Gr^{1/3}$
Mong (1977) Text book	$Nu = 0.474 Gr^{1/4}$ (from Ostrach, 1952)	$Nu = 0.018 Gr^{2/5}$ (from Eckert and Jackson, 1950)
Welty (1978)  Text book	$Nu = 0.478 Gr^{1/4}$ (theoretical solution) $Nu = 0.509 Gr^{1/4}$ (from Eckert and Jackson, 1951) $Nu = 0.503 Gr^{1/4}$ (from an integral analysis by Eckert, 1951)	$Nu = 0.018 Gr^{2/5}$ (from Eckert and Jackson, 1950)
Alander and Hammond (1983) Review paper	$h_c = \left\{ \left[ 1.5 \left(\frac{\Delta T}{L}\right)^{1/4} \right]^4 + \left[ 1.23 (\Delta T)^{1/3} \right]^4 \right\}^{1/4}$	

**Fig. 2.6:**  
*Correlations for surface convective heat transfer from various literature sources*  
*(After Halcrow - 1987)*

Finally, it should be emphasized that in practice two approaches may be applied to determine the space and time averaged htc's; (1) the engineering approach which involves the use of values recommended by the CIBSE Guide - Section A3 and (2) the models proposed by different workers such as Alamdari and Hammond (1983).

#### **Determination of the convective heat transfer coefficient (htc) for natural convection as applied to buildings**

The convective htc is a complex and variable quantity depending on the geometry of the surface, on the flow characteristics as well as on the physical properties of the fluid. It is not a transport property like the thermal conductivity. Its determination constitutes the central problem of convective heat transfer.

Gates (1962) mentions that the problem of determining  $h_c$  is often difficult since it involves a number of factors describing the geometry and physics of the particular problem. Gates indicates that the convection coefficient depends upon:

- (1) the shape (flat or curved), orientation (horizontal or vertical), roughness and dimensions of the surface
- (2) the physical properties of the fluid (density, viscosity, specific heat and thermal conductivity)
- (3) whether the velocity of the fluid is small enough to give rise to laminar flow or large enough to give rise to turbulent flow
- (4) temperature difference between the surface and the fluid

There exist several methods for the determination of  $h_c$ . Kreith (1973) has described four:

- (1) mathematical solutions of the continuity, momentum and energy equations
- (2) approximate boundary layer analysis based on integral techniques
- (3) dimensional analysis combined with experimental data
- (4) an approach which relies on the analogy between heat, mass and momentum transfer.

The  $h_c$  values are temporally and spatially variable. Because of dependencies such as its height and the constraints at the corners, along with time variations in the existing conditions such as variations in the external temperature, it is highly unlikely that uniform boundary conditions ever exist over a plain section of the wall. Consequently, time and space averaged values are normally used in building heat transfer calculations.

The value recommended by the CIBSE Guide - Section A3 for the internal surface convective htc for natural convection is  $3.0 \text{ W/m}^2\text{K}$ . The air speed at the surface is assumed to be not greater than  $0.1 \text{ m/s}$  and the heat flow direction is horizontal. No allowance has been made



for the possible increase in  $h_c$  which might occur with a significant airflow created by infiltration, ventilation etc., where the heat transfer by convection becomes more complex.

A general expresssion for representing the natural convection exchange at the wall surfaces of a room taking into account the geometry and the temperature difference between the room air and the wall surface (applicable to vertical surfaces) is the correlation proposed by Alamdari and Hammond (1983) who state that "in the context of the built environment the physical properties of air do not vary greatly". The expression encompasses most of the flow conditions found within buildings and provides a smooth fit to data across the full range of laminar, transitional and turbulent airflows.

$$h_c = [ \{ a (\Delta T/L)^p \}^m + \{ b (\Delta T)^q \}^m ]^{1/m} \tag{2.5}$$

where

- $h_c$  = surface-averaged heat transfer coefficient (W/m<sup>2</sup>K)
- $\Delta T$  = temperature difference between the air and the wall surface (K)
- $L$  = characteristic length of heat transfer surface (m)

and  $a=1.5, b=1.23, p=0.25, q= 0.333, m=6$

Commenting on Eq. 2.5, Alamdari and Hammond (1983) also quote that "the temperature variations experienced in buildings imply that the convection coefficient obtained from Eq. 2.5 is unlikely to differ by more than +/-4%". However, the convective htc may vary between 1.37 and approximately 4.0 W/m<sup>2</sup>K for a temperature difference of 1 and 20 K respectively. These values are in a reasonably good agreement with the values quoted in the Halcrow report (1987) which are 1.0 and 5.4 W/m<sup>2</sup>K for the same temperature differentials as above.

A number of correlations for surface convective heat transfer from various literature sources is presented in Fig. 2.6. Most appropriate for this study however are the separate expressions for laminar and turbulent flow over a vertical plate (see chapter 5 - section 5.1.3) given by Rogers and Mayhew (1980) in Table 2.1.

	Average $h_c$ [W/m <sup>2</sup> K]	
	Laminar or Transition	Turbulent
	$10^4 < Gr < 10^9$	$10^9 < Gr < 10^{12}$
Vertical plate of height $L$	$1.42 (\Delta T/L)^{1/4}$ [K/m]	$1.31 (\Delta T)^{1/3}$ [K]
<b>Table 2.1:</b> <i>Simplified equations for free convection heat transfer coefficients in air at atmospheric pressure</i> <span style="float: right;"><i>(After Rogers and Mayhew - 1980)</i></span>		

### 2.3.2 Radiation

Thermal radiation is electromagnetic energy in the infrared part of the spectrum, whose wavelength is a function of the temperature of the emitter. Radiative heat transfer in the environment is governed by the absorption, scattering and reflection properties of the atmosphere and natural surfaces. The fractions of the radiation absorbed, reflected and transmitted are called the absorptivity,  $\alpha$ , the reflectivity,  $\rho_r$ , and the transmissivity,  $\tau$ , respectively:  $\alpha + \rho_r + \tau = 1$ . Most solids are opaque to thermal radiation, in which case the transmissivity is zero:  $\alpha + \rho_r = 1$ .

The energy of thermal radiation for any given temperature varies with wavelength and with the nature of the surface. A perfect radiator, or black-body as it is termed, has an absorptivity of unity. The calculation of thermal radiation is based on the Stefan-Boltzmann law, which gives the emissive power of a black-body as a multiple of the fourth power of the surface absolute temperature:

$$E_b = \sigma T^4 \quad (2.6)$$

where  $E_b$  and  $T$  are expressed in ( $\text{W}/\text{m}^2$ ) and ( $^\circ\text{C}$ ) respectively.  $E_b$  is the energy radiated per unit time and per unit area by the ideal radiator or black-body, and  $\sigma$  is the Stefan-Boltzmann constant, which has the value  $\sigma = 5.7 \times 10^{-8} \text{ (W/m}^2\text{K}^4\text{)}$ .

The heat flux emitted by a real surface is less than that of the ideal radiator and is given by:

$$E_b = \epsilon \sigma T^4 \quad (2.7)$$

where  $\epsilon$  is a radiative property of the surface called the emissivity. This property indicates how efficiently the surface emits compared to an ideal radiator.

In the thermal design of the fabric the rate of heat loss through heat transfer by radiation is important. The rate at which heat transfer by radiation takes place depends on:

- (1) the emissivity of the surface
- (2) the temperature of the surface
- (3) the temperature of the surroundings.

For a given surface, the larger the temperature difference between the surface and its surroundings the greater the rate of heat loss by radiation. The radiative processes, to which a building is subjected to, are divided into longwave and shortwave (solar).

## Longwave radiation

Heat is exchanged between the room surfaces by longwave radiation which depends strongly on the surface geometries and orientations, as well as on their radiative properties and temperatures.

The thermal radiation emitted from a surface is a function of its absolute temperature and surface emissivity. Energy exchange between surfaces take place when they are maintained at different temperatures. In this case the emissions form a net radiation energy exchange. With two or more surfaces at different temperatures heat will be emitted, absorbed and reflected by each surface (assuming that the surfaces are opaque and transmission is non-existent). This exchange between the surfaces depends not only upon surface properties and absolute temperature of each surface but also on their relative positions.

Consequently, the problem becomes essentially one of determining the amount of energy which leaves one surface and reaches the other. To solve the problem the concept of the radiation form factors is introduced.

$F_{1-2}$  = fraction of energy leaving surface 1 and reaching surface 2

$F_{2-1}$  = fraction of energy leaving surface 2 and reaching surface 1

$F_{m-n}$  = fraction of energy leaving surface m and reaching surface n

For two black-body surfaces at different absolute temperatures, the energy leaving surface 1 and arriving at surface 2 is:  $E_{b1}A_1F_{1-2}$

The energy leaving surface 2 and arriving at surface 1 is:  $E_{b2}A_2F_{2-1}$

Since the surfaces are black, all the incident radiation will be absorbed, and the net energy exchange is:  $E_{b1}A_1F_{1-2} - E_{b2}A_2F_{2-1} = Q_{1-2}$

If both surfaces are at the same temperature, there can be no heat exchange, that is,  $Q_{1-2} = 0$ .

Also  $E_{b1} = E_{b2}$ , consequently

$$A_1F_{1-2} = A_2F_{2-1} \quad (2.8)$$

The net heat exchange is therefore:

$$Q_{1-2} = A_1F_{1-2} (E_{b1} - E_{b2}) = A_2F_{2-1} (E_{b1} - E_{b2})$$

Eq. 2.8 is known as a reciprocity relation, and it applies in a general way for any two surfaces m and n:  $A_mF_{m-n} = A_nF_{n-m}$



Although the relation is derived for black surfaces, it holds for other surfaces also as long as diffuse radiation is involved.

In actual applications, exact calculation of radiative energy exchange in an enclosure is extremely difficult because of the complicated surface geometries, the directionally and spectrally dependent surface radiation properties, and the often mixed diffuse and specular radiation characteristics of surfaces (Rogers and Mayhew - 1980). Real surfaces often involve surface imperfections such as roughness, oxidation and dust or grease contamination, which affect both the magnitude and the directional characteristics of surface emission, absorption and reflection. In general, reasonable assumptions and approximations should be introduced to any particular problem, since the attainment of an exact calculation is neither practical nor desirable.

Consider a region within which there is black-body radiation characterised by a temperature  $T_e$ . Typically, such a region may be found within an enclosed space such as a room whose walls have a uniform temperature  $T_e$ . The radiation properties of the enclosing walls may be arbitrary. A body is situated at a wall facing the outside environment at temperature  $T_s$  which is lower than  $T_e$  having arbitrary radiation properties. This body is sufficiently small relative to the size of the enclosure so that its presence does not change the black-body radiation field.

The radiant energy emitted per unit time and area by the body is  $\epsilon\sigma T_s^4$ , while the corresponding absorbed radiant flux is  $\alpha\sigma T_e^4$ . Consequently, the net rate of radiant outflow  $Q$  is

$$Q/A = \epsilon\sigma T_e^4 - \alpha\sigma T_s^4$$

where  $A$  is the surface area of the body. This expression holds regardless of the directional and spectral properties of the body. For the grey-body condition ( $\epsilon = \alpha$ ), it follows:

$$Q/A = \epsilon\sigma (T_e^4 - T_s^4) \quad (2.9)$$

Eq. 2.9 can be applied to a grey body in either a black, or very large enclosure (compared to the body). Except for the simple case of radiation exchange between a grey body and an enclosure, the treatment of grey-body radiation is difficult, since the effect of reflected energy must be taken into consideration.

**Determination of the radiative heat transfer coefficient (htc) as applied to buildings**

As with the convective htc, the radiative htc is also highly variable temporally and spatially over the wall surface. Consequently, time and space averaged values are used since the distribution of the radiative htc is not uniform over the wall surface area. The radiation coefficient is strongly dependent on the temperature and the geometry of the surfaces.

In order to express the radiation mode in a manner similar to convection, the radiation rate equation has to be linearised, that is, making the heat rate proportional to a temperature difference. Thus by introducing a radiation coefficient  $h_r$  the expression for calculating the net heat transfer rate can be written as:

$$Q = A h_r (T_e - T_s) \text{ [W]}$$

where

$$h_r = \epsilon \sigma (T_e + T_s) * (T_e^2 + T_s^2) \text{ [W/m}^2\text{K]}$$

Table 2.2 indicates the values recommended by the CIBSE Guide - Section A3 for the internal surface radiative htc for a range of surface temperatures.

Temperature of the radiating surface (°C)	$h_r$  (W/m <sup>2</sup> K)
0	4.6
10	5.1
20	5.7
<b>Table 2.2:</b> <i>Radiative htc (<math>h_r</math>)</i> <i>(After CIBSE Guide - 1986)</i>	

The above values are in good agreement with the values quoted in the Halcrow report (1987) where it is mentioned that "neglecting the possible use of low emissivity coatings or blinds on the inside surface of the windows, the radiative htc is likely to lie in the range from 4.6 to 5.1 W/m<sup>2</sup>K". Table 2.2 also indicates that the stability of the radiative htc values is considerably higher when compared to the convective htc values.

## 2.4 Applicability of heat transfer processes in practice

The total htc can be written as the sum of the convective  $h_c$  and the radiative  $h_r$ , i.e.

$$h_{tot} = h_c + h_r$$

and when both convective and radiant losses occur simultaneously, a simple equation may be used to represent the two processes of heat transfer in a cuboid room:

$$Q = A * (h_c + h_r) * (T_1 - T_2) \quad [W] \quad (2.10)$$

where

$T_1$  = air temperature which is approximately equal to the  
mean temperature of the surrounding environment  
(mean temperature of the five surfaces in the room)

and

$T_2$  = mean internal surface temperature of the external wall

In the engineering approach (Eq. 2.10) combined time and space averaged htc's are also employed as in the case of convective and radiative htc's. Table 2.3 indicates the standard values recommended by the CIBSE Guide - Section A3 for the internal surface resistance ( $R_{si}$ )/combined htc applicable to walls for horizontal heat flow.



	High emissivity factor	Low emissivity factor
Combined htc (m <sup>2</sup> K/W)	8.33	3.33
Surface resistance (W/m <sup>2</sup> K)	0.12	0.30
<p><b>Notes:</b></p> <p>(1) High emissivity factor assumes <math>\epsilon_1 = \epsilon_2 = 0.9</math></p> <p>(2) Low emissivity factor assumes <math>\epsilon_1 = 0.9, \epsilon_2 = 0.05</math></p> <p>(3) Air speed at the surface is assumed to be not greater than 0.1 m/s</p> <p>(4) <math>\epsilon_1</math> and <math>\epsilon_2</math> are the emissivities of surfaces involved  <math>\epsilon_1</math> is the emissivity of the surface/other surfaces to which it radiates and  <math>\epsilon_2</math> is the emissivity of the radiating surface</p>		
<p><b>Table 2.3:</b></p> <p><i>Internal surface combined htc/resistance values</i></p> <p><i>(After CIBSE Guide - 1986)</i></p>		

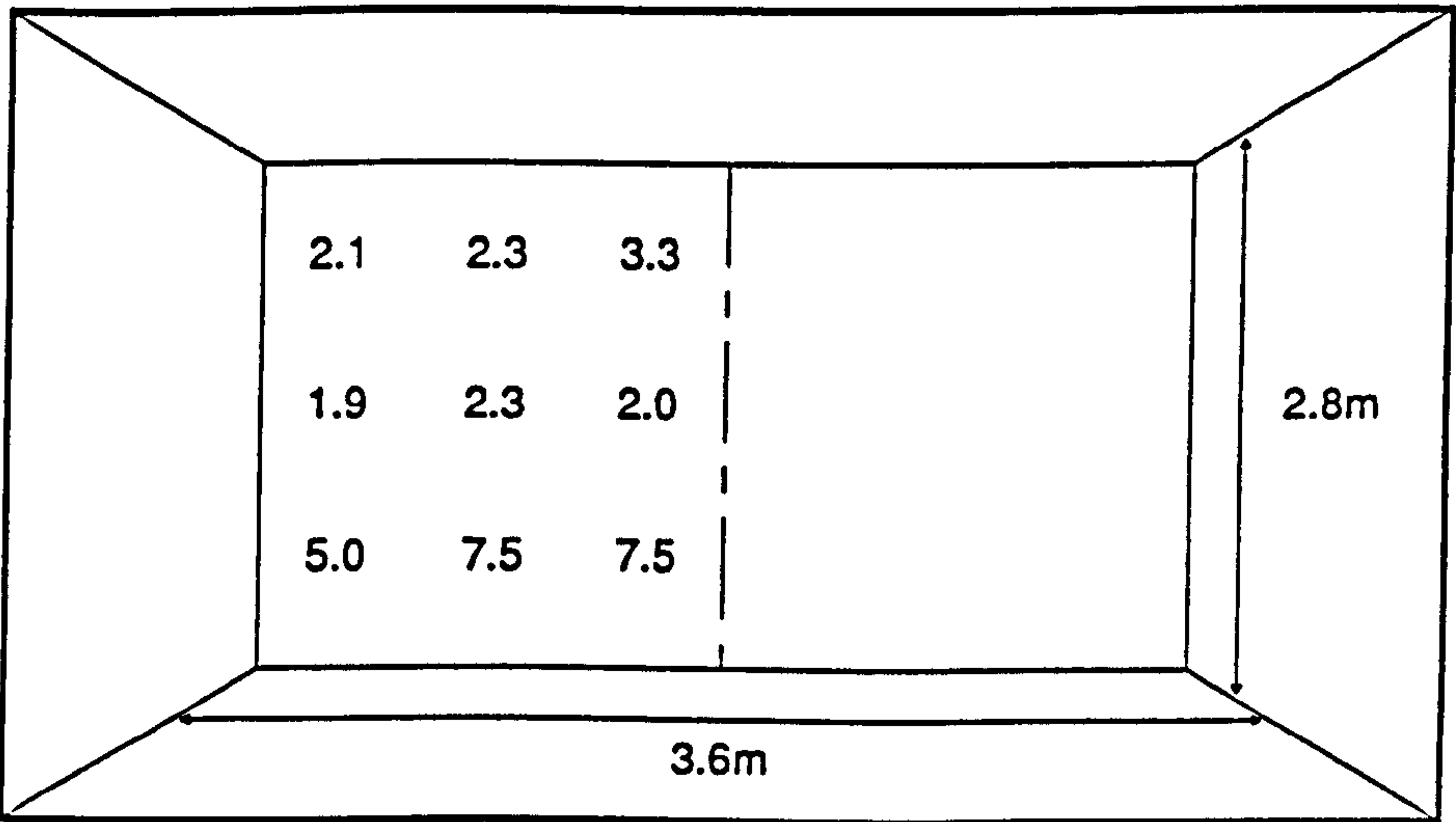
According to the Halcrow report (1987) the combined htc may vary from 6.1 to 10 W/m<sup>2</sup>K for a temperature difference between wall surface and air of 1 to 20 K respectively. Higher values of the radiative htc will usually coincide with lower values of the convective htc's (Halcrow - 1987). In other words the combined htc is relatively stable and the standard value of 0.12/8.33 for the internal surface resistance ( $R_{si}$ )/combined htc applicable to walls for horizontal heat flow is normally used in heat transfer calculations.

What is likely to happen in practice is that the boundary conditions are highly variable, temporally and spatially.

In the context of the present study, although the whole concept of uni-dimensional heat flow in a building wall may be applied, spatially uniform boundary conditions do not exist, consequently uniform wall temperatures will not normally exist as the driving forces for heat flow.

Spatially the htc values are difficult to establish as Fig. 2.7 indicates, but, as far as heat flow measurements are concerned, the assumption is that the combined htc may be considered to be sensibly constant within the smaller area in which the heat flow measurement is made.

Temporally, the htc values are just as difficult to establish, but, as far as heat flow measurements are concerned, the assumption is that the boundary conditions are the same over the sensor and the surrounding wall surface. Consequently the temporal variation does not introduce uncertainty into the measurement of wall transmittance.



**Fig. 2.7:**  
*Variation of combined surface heat transfer coefficient over the test wall*  
*- [Spatial distribution] (After Valentine et al - 1989)*

## 2.5 Solar (Shortwave) radiation

The wavelength distribution of solar radiation is strongly dependent on atmospheric conditions, time of the year, and the angle of incidence for the sun's rays on the surface of the earth. Due to atmospheric effects, the solar radiation at the earth's surface consists of two components:

- (i) Direct radiation which is received from the sun without change of direction.
- (ii) Diffuse radiation, the portion received from throughout the sky after its direction has been changed by reflection and scattering in the atmosphere.

The major portion of solar energy is concentrated, in the visible, infrared and a minor proportion of ultra-violet wavelength regions. Meteorologists and hydrologists use the term insolation to describe the intensity of solar radiation, usually shown as  $I_s$ , where  $I_s$  is a combination of direct + diffuse radiation. If  $\alpha_s$  is the absorptivity of the material, the amount of shortwave radiation absorbed by a body is:  $\alpha_s I_s$ .

Solar radiation is absorbed at the external surface of a wall where it is transformed to low temperature heat and is redistributed by conduction into the wall material, convection to the air and longwave radiation to other surfaces. The radiant heat that they emit, however, is low temperature or longwave radiation which cannot be transmitted back to the outdoor environment through the glass because the glass is opaque to longwave radiation.

At short wavelengths the values of the spectral properties of a surface may be considerably different from values at long wavelengths. Solar radiation is concentrated in the short wavelength region of the spectrum, whereas surface emission is at much longer wavelengths, which means that the solar absorptivity  $\alpha_s$  of a surface may differ from its emissivity  $\varepsilon$ . Appropriate values for different building materials may be found in several textbooks.

Where windows are concerned the mean solar heat gain into a room is a function of the mean solar irradiance and is given by:

$$Q_s = S_e * I_T * A_g \quad (2.11)$$

where

$Q_s$  = mean solar gain (W)

$I_T$  = mean total solar irradiance ( $W/m^2$ )

$S_e$  = mean solar gain factor

$A_g$  = area of glazing ( $m^2$ )

Corresponding values may be taken from Tables provided by Section A of the CIBSE Guide.



## **2.6 Prediction of building fabric performance**

The complex transient 3D heat transfer processes that an enclosure in general, and the external wall envelope in particular are subjected to, may be simplified to 1D by making certain assumptions. The simplification is an engineering approach which is mainly made for ease of calculation procedures for the estimation of the heat losses through the wall. While the engineering approach ignores the dynamic behaviour of the wall, there are several methods that take it into account. If a detail representation is required therefore, more complex modelling techniques must be employed.

A number of methods exist for investigating energy exchanges and predicting the performance of the building fabric. Although steady state methods are useful for predicting mean heat flows, it is unsuitable for examining how net energy exchanges fluctuate from hour-to-hour as a result of perturbations in the external and internal climates. To achieve this degree of detail it is necessary to use techniques capable of solving transient heat flow problems.

Several thermodynamic processes occur simultaneously on the external wall of a building which affect to a great extent the heat flow through the wall. The problem of representing the dynamic and 3D heat flow through the external wall is highly complicated because of the number of parameters involved and the uncontrollable external boundary conditions (heat transfer coefficient, solar radiation, wind speed, moisture content of the brick etc.).

Nevertheless, steady state and transient heat flow may be represented by models of varying complexity (see for example, Hanna - 1974, Clarke - 1985). Each model is concerned, at its own level, to satisfy the first and second laws of thermodynamics. The flexibility of the modelling technique is determined by the manner in which this network is treated mathematically, for example some portion may be neglected, fixed values may be assigned to varying parameters or simplifying boundary conditions may be assumed.

### **Thermal modelling techniques for opaque building elements**

The mathematical representation of physical (real) processes is embodied in the title "thermal modelling". A thermal model of a building or a building element is the description of the interactions of these real processes by means of mathematical formulae. Most existing models fall into one of the following three categories: analytical, numerical, experimental (Fig. 2.8).

The modelling of the thermal performance of buildings or building elements by experimental techniques can be taken as either:

- (i) constructing a model to represent the real thermal situation in an analogous way (Fig. 2.8). Prior to the advent of digital computers, the use of electrical and hydraulic analogues to study non-steady state heat flow was one of the main methods but has now been superseded by powerful computer packages.

or

- (ii) physically constructing a full size or scaled model of the real building and performing measurements in real time, or performing measurements in real buildings as is the case in the present study.

The advantages of a model of type (i) over a model of type (ii) are fairly obvious, namely that the cost, flexibility, scope of detailed study, time factor and so forth tend to restrict or prohibit experiments of the second type (see also Table 2.4).

A description of the experimental techniques (type i) may be found in a number of references: Moore (1936), Billington (1951), Stephenson and Mitalas (1961, 1962, 1963), Day and Burberry (1976).

Analytical and numerical techniques are mainly computational techniques. They usually involve a large number of mathematical calculations which renders their use suitable for digital computers and they represent a wide range of accuracy and flexibility levels. Table 2.4 indicates the advantages and disadvantages of the computational techniques.

A description of the main computational techniques which have been developed to model the thermal behaviour of buildings may be found in a number of references: Van Gorpum (1950), Gaumer (1962), Mitalas and Stephenson (1967), Waters (1970), Kusuda (1976), Muncey (1979).

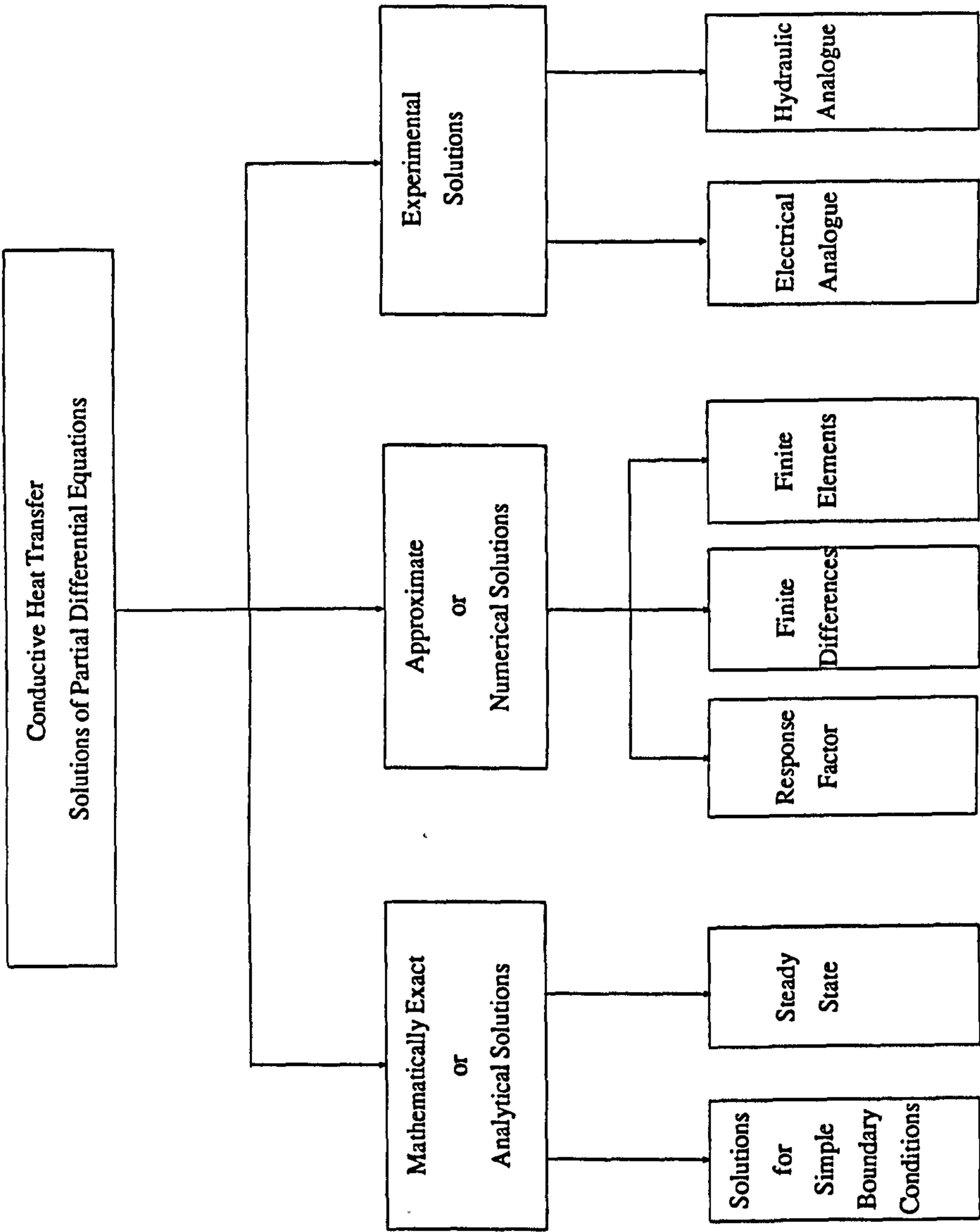
In the context of the present study, two models were found to be most appropriate:

- (a) The steady state one dimensional model (Analytical techniques - Fig. 2.8), which is mainly a design calculation recommended by the CIBSE Guide - Section A3 (1986), in order to establish how the wall element is expected to perform.

- (b) An appropriate model had also to be found for the level of complexity involved, so that the wall construction of every site investigated in the field could be modelled in more detail by establishing the complex heat flow patterns through the component. Finite differences and finite elements (Numerical techniques - Fig. 2.8) were found to be most appropriate for the needs of the study, i.e. modelling a wall construction at 3D, steady state, and fixed boundary conditions. Finite elements (FE), were most appropriate to use, the reasons being:

The FE method requires that at any discontinuity in any factor (such as  $h_{tc}$ , material properties, etc.) relating to the value of the field variable (temperature), must lie at the boundary to an element. Therefore, conveniently the FE procedure provides the values of temperatures at the boundaries of regions of interest, which in this investigation allowed for a rapid evaluation of the heat flux at the sensor location. In addition, the FE solution technique gives a direct solution via the matrix solution of simultaneous equations and not an iteration solution as it is the case in the finite difference solution. Thus, although the FE solution is strongly dependent on the mesh specification, the possibility of poor convergence or numerical instability is avoided (Armstrong - 1990).





**Fig. 2.8:**  
*Thermal modelling techniques*

METHOD	ADVANTAGES	DISADVANTAGES
STEADY STATE ('U' VALUE) 1-D only	The 'U' value model is a relatively easy and well established method to use, which involves only simple manual calculations. An experienced user can, with adequate data, obtain estimates of heating requirements over a long period with the degree-day method.	Steady-state methods either ignore or grossly simplify the dynamic response of the building fabric. Internal heat flows, solar gains, casual gains, longwave radiation exchanges, plant operational strategies, etc., are either not included or greatly simplified. Method can only be used for varying boundary conditions using time-averaged values (e.g. degree days). They are totally inadequate for looking at detailed behaviour on short timescales.
ANALYTICAL SOLUTIONS	They can be used to check the accuracy of certain calculations made in dynamic numerical problems. Also, the derivation and solution of equations from first principles can give a better insight into a problem in a way which empirical relationships derived from repeated numerical simulations cannot.	Solutions are limited in scope to a small number of simplified and unrealistic types of input and tend to be very specific to a problem. They are often difficult to calculate and the complexity of solutions increases rapidly with the complexity of the problem. Few analytical solutions are available for constructions of more than one or two homogeneous layers in 1 Dimension.
HARMONIC OR MATRIX 1-D only	Exact output result for homogeneous layers (only for sinusoidal inputs). Realistic representation for unsteady state. Short run time (very short run times are possible which allow a wide range of fabric properties to be investigated quickly).	The method is inflexible in dealing with internal or changing heat flows. Non-sinusoidal inputs must be represented using fourier series. This is impractical when specifying a wide variety of boundary conditions and can lead to "clipping" errors for discontinuously changing boundary conditions.

Table 2.4:  
*Advantages and disadvantages of thermal modelling techniques*

METHOD	ADVANTAGES	DISADVANTAGES
RESPONSE FACTOR 1-D only	<p>Less run time required than most of the other methods. Any type of meteorological data can be used. Possible to handle multi-layered constructions. The results of validation exercises have shown that under suitable conditions, the method can provide an accurate model of thermal behaviour. It is particularly suitable for air-conditioned buildings with many similar rooms, such as office blocks. Once the response factors have been calculated, for each construction type, simulations are very rapid.</p>	<p>Calculation of response functions is quite complicated and they are specific to a given timestep. May be unrealistic for complicated situations. Usually one hour time interval used. However, the restriction of a fixed timestep causes difficulties in modelling HVAC equipment and controls which have much shorter time constants. Shorter timesteps can, of course, be used, but this requires the recalculation of all the response factors and could lead to data storage problems if a range of timesteps, each with a set of response factors for several constructions, were to be available. The main disadvantage is the apparent inability to simultaneously model thermally connected zones under separate controls.</p>
FINITE DIFFERENCE 1D, 2D or 3D	<p>Fewer assumptions need to be made than with other methods except finite elements. Special features can be added into the network independently, provided their inputs are in terms of temperatures or heat fluxes at nodes. This is useful for plant simulations. No lengthy calculations are necessary before a run can begin. The fabric specifications can be altered (for example, by adding an extra layer to a wall) without there being any wall indices requiring recalculation. No difficulties arise when modelling adjacent zones with independent controls which exchange heat by conduction, ventilation and possibly radiation. Variety of input of meteorological data. Variety of output information with small time increments.</p>	<p>Substantial computing power required for the solution of the matrix of equations at each timestep, particularly for simulations of months or a year. However, this problem is diminishing as computer technology advances rapidly. Irregular shapes cannot easily be represented in 2-D and 3-D. Long simulation times compared to some other methods. Some solution techniques (e.g. explicit method) require short timesteps to maintain numerical stability, resulting in long simulations.</p>

Table 2.4:

(continued)



METHOD	ADVANTAGES	DISADVANTAGES
FINITE ELEMENTS 1D, 2D or 3D	Its ability to model a structure of arbitrary geometry in 1, 2 or 3 dimensions. Its ability to accommodate arbitrary boundary conditions and multi-dimensions. Its ability to model composite structures. Most suitable for investigating individual constructions in detail over short time intervals, e.g. cold bridges.	Requires high quality commercial programs to achieve satisfactory results. Experience and judgement are needed in order to construct a good finite element model. Impractical for full scale simulation of whole buildings in 2 or 3 dimensions over long time intervals, due to complexity of setting up input data and long run time.
<u>EXPERIMENTAL</u> ELECTRICAL ANALOGUE Normally 1-D but can be 2 or 3-D	Able to simulate complex interactions very rapidly using electrical resistance-capacitance networks. Simple networks used in teaching building physics.	Not suitable for design due to the effort and expertise needed to create a model. Each model must be physically built from components, which is a very slow process for a complex building. Boundary conditions must be generated electronically and are therefore usually cyclic or must be specially generated from data stored electronically. Now largely superseded by digital computer simulations.

Table 2.4: (continued)

# **FIELD MEASUREMENTS**

## **CHAPTER 3**

### **3.0 Introduction**

This chapter presents a review of methods and equipment used to recover the thermal transmittance value of wall constructions in order to establish a set of appropriate conditions for field measurements.

### **3.1 Methods used to establish the transmittance value of the wall**

The experimental methods used to establish the thermal transmittance value of the wall, in both laboratory and the field, fall into the three main categories of Thermography, Hot Boxes, Heat Flux Sensors and Temperature Sensors.

#### **3.1.1 Thermography**

Thermography is based on detection of infrared radiation emitted by solid bodies. A recent comprehensive review of how an infrared camera may be used with regard to detecting thermal defects in, and determining the heat losses through, the building envelope is given by Valentine et al (1989).

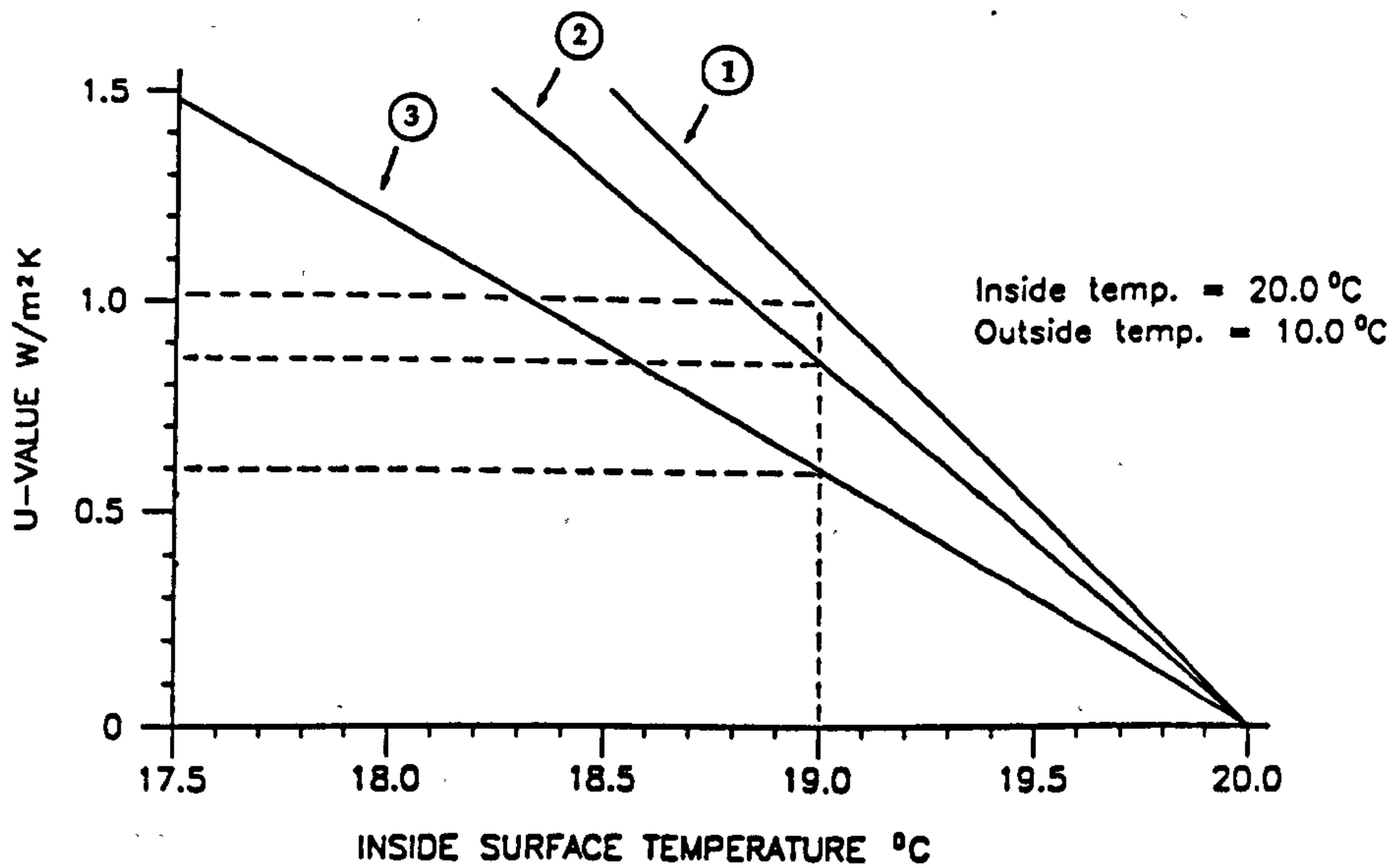
The advantages are that it is rapid and non-destructive. Nothing is attached to the wall surface and consequently the surface conditions are left undisturbed. In addition thermography enables relatively large areas to be inspected in detail simultaneously. The equipment used is relatively compact and portable.

Using the infrared camera to establish the heat losses through the external building envelope is not a standardized procedure due mainly to the problems associated with the variability of the surface heat transfer coefficients (htc's). The method is sometimes used however, because of its relative simplicity (Kaplan - 1978, Munis and Grot - 1978).

The determination of the U value relies upon knowledge of the heat transfer coefficients (htc's). The disadvantages are that the htc's may be variable during the monitoring period, in both space and time; a matter which has nothing to do with the underlying construction of the wall. The consequences are shown in Fig. 3.1 which indicates that for the same surface temperature of the wall (19 °C) and for three different htc's (6.0, 8.1, 10.0 W/m<sup>2</sup>K), there are three different U values of 0.6, 0.88, 1.0 W/m<sup>2</sup>K respectively.

There is an additional error due to the instantaneous reading which does not take into account the thermal storage in the wall fabric. This is superimposed on the previous error resulting from the variability of the htc's. From the foregoing discussion, it is clear that thermography is essentially a qualitative method.





$$\textcircled{1} = R_{si} = 0.100 \text{ m}^2\text{K/W}$$

$$(10.0 \text{ W/m}^2\text{K})$$

$$\textcircled{2} = R_{si} = 0.123 \text{ m}^2\text{K/W}$$

$$(8.10 \text{ W/m}^2\text{K})$$

$$\textcircled{3} = R_{si} = 0.169 \text{ m}^2\text{K/W}$$

$$(6.00 \text{ W/m}^2\text{K})$$

where  $R_{si}$  is the surface resistance value at the internal surface of the wall and the number in ( ) is the corresponding heat transfer combined coefficient (htc).

**Fig 3.1:**

*Effect of the variation of htc's on the U value*  
(Based on Valentine et al - 1989)

For the reasons outlined above the use of infrared cameras in order to find the thermal transmittance of a wall construction was found to be unsatisfactory by Siviour and McIntyre (1982), Valentine et al. (1989). Therefore, the use of thermography is mainly limited to investigating building defects (Treado - 1980, Siviour and McIntyre - 1982, Anderson - 1984-I, Valentine et al. - 1989).

### **3.1.2 Hot boxes**

Hot boxes may be used to measure the heat flow through built-up wall sections. This is a well established laboratory procedure in which the specimen to be tested is built in a frame and placed between two well-insulated chambers. There are two main types: the Guarded Hot Box (GHB, Fig. 3.2) and the Calibrated Hot Box (CHB, Fig. 3.3).

Hot Boxes have been used in several laboratories such as, National Bureau of Standards, Owens-Corning Fibreglass, Portland Cement Association, Pilkington Brothers - Research and Development Laboratories etc., (Sherman et al - 1983). A number of standards has been developed to determine thermal transmission properties for built-up sections and insulation specimens (De Ponte - 1987).

BS 874:Part 3 (1986), the "Standard Methods for Determining Thermal Insulating Properties" is used in UK. Details about the apparatus used, measurement methods of these systems, advantages and disadvantages may be found in Mumaw (1974), Orlandi et al (1983), Goss and Olpak (1983), Lavine et al (1983), Guy and Nixon (1987), McCaa et al (1987), Van Geem (1987). An obvious disadvantage of the large hot box is its size (usually 3 \* 3 m approximately). This makes it suitable for laboratory use only.

Several portable variations of the guarded hot box have been developed, in order to evaluate the thermal properties of building components in the field. Isaacs and Trethowen (1985) state that in 1950 Bastings and Benseman used a transportable guarded hot box to measure 42 walls on site with R values ranging from 0.21 to 1.35 m<sup>2</sup>K/W. However, this method was not suitable for use in fluctuating conditions, required very experienced operators, and each equipment set measured only one element at a time.

A device which is similar to a guarded hot box, was developed by Brown and Schuyler (1979) of the Building Research Division (National Research Council of Canada). This device was a calorimeter which consisted of a five sided insulated box, the open side of which is sealed against the specimen to be measured. The metering area is 1.2m by 2.1m and the calorimeter is placed on the inside of a wall so that the conditions at the exterior of the wall are not altered during the measurement (Fig. 3.4). This device has the advantage of being usable with laterally non-uniform walls but has the disadvantages of being rather bulky and requiring careful control of the interior temperatures during measurements.



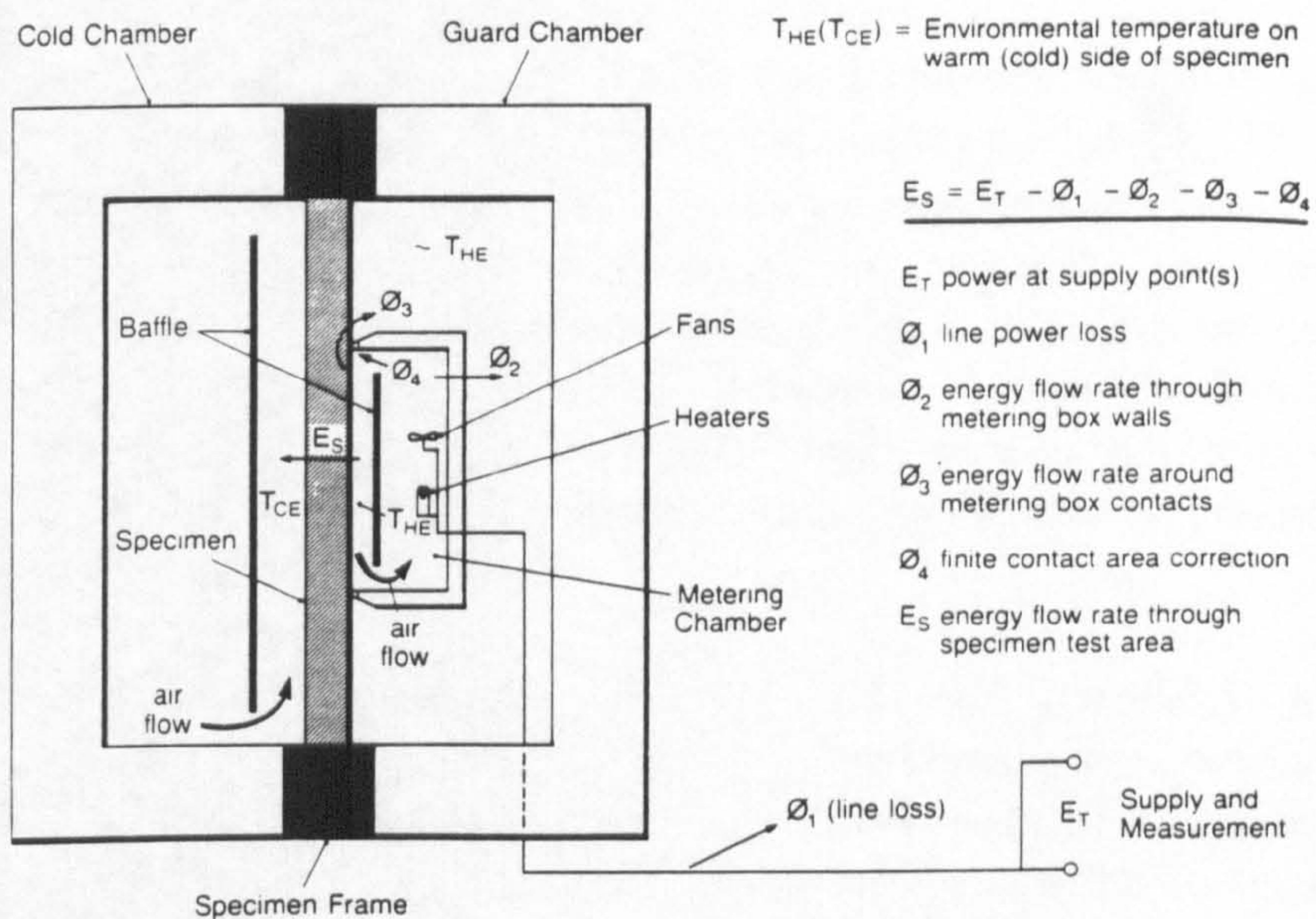


Fig. 3.2:

Schematic of a guarded hot box and its energy flows

(After Guy and Nixon - 1987)

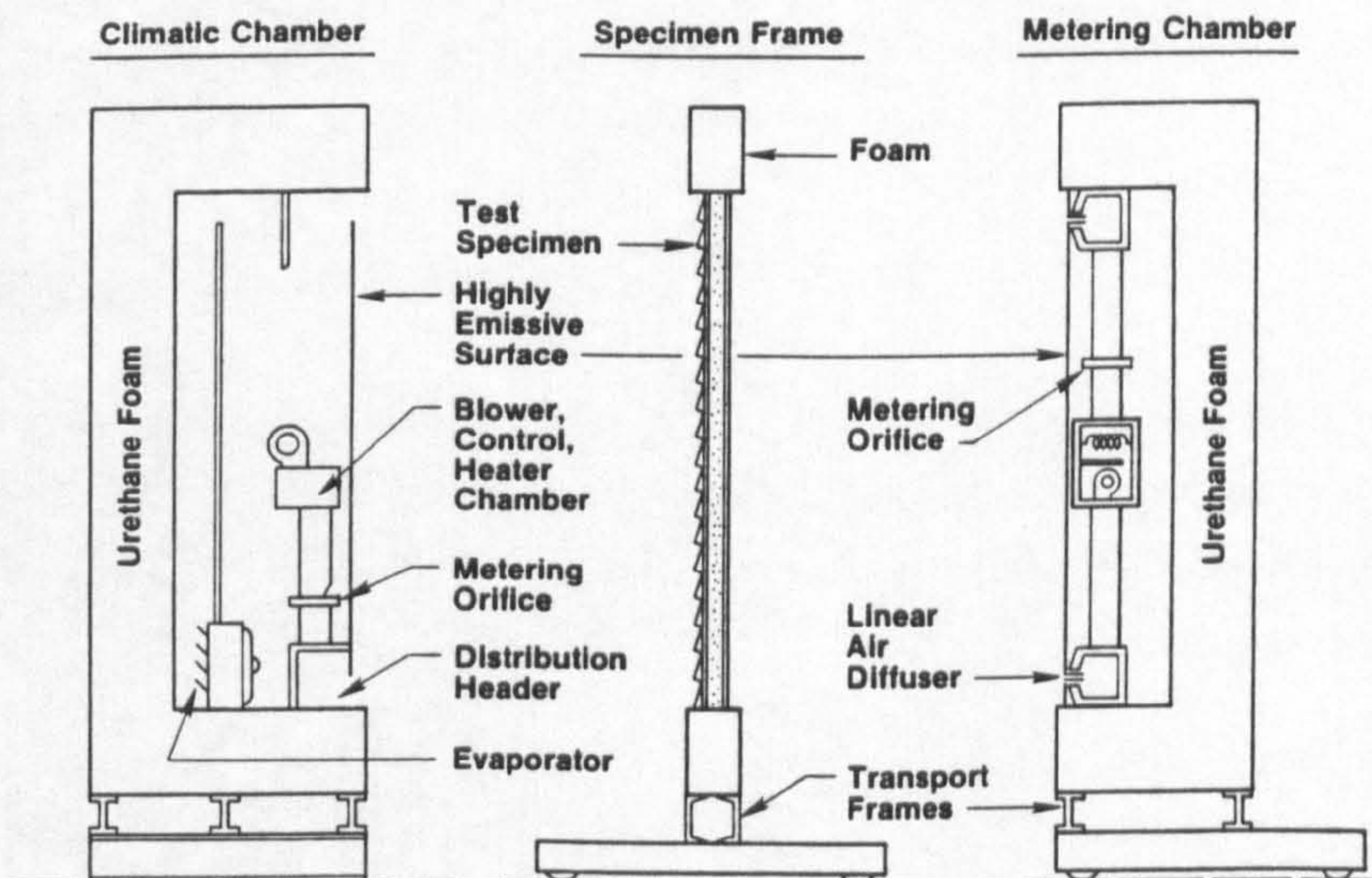


Fig. 3.3:

Schematic of a calibrated hot box

(After Lavine et al - 1983)



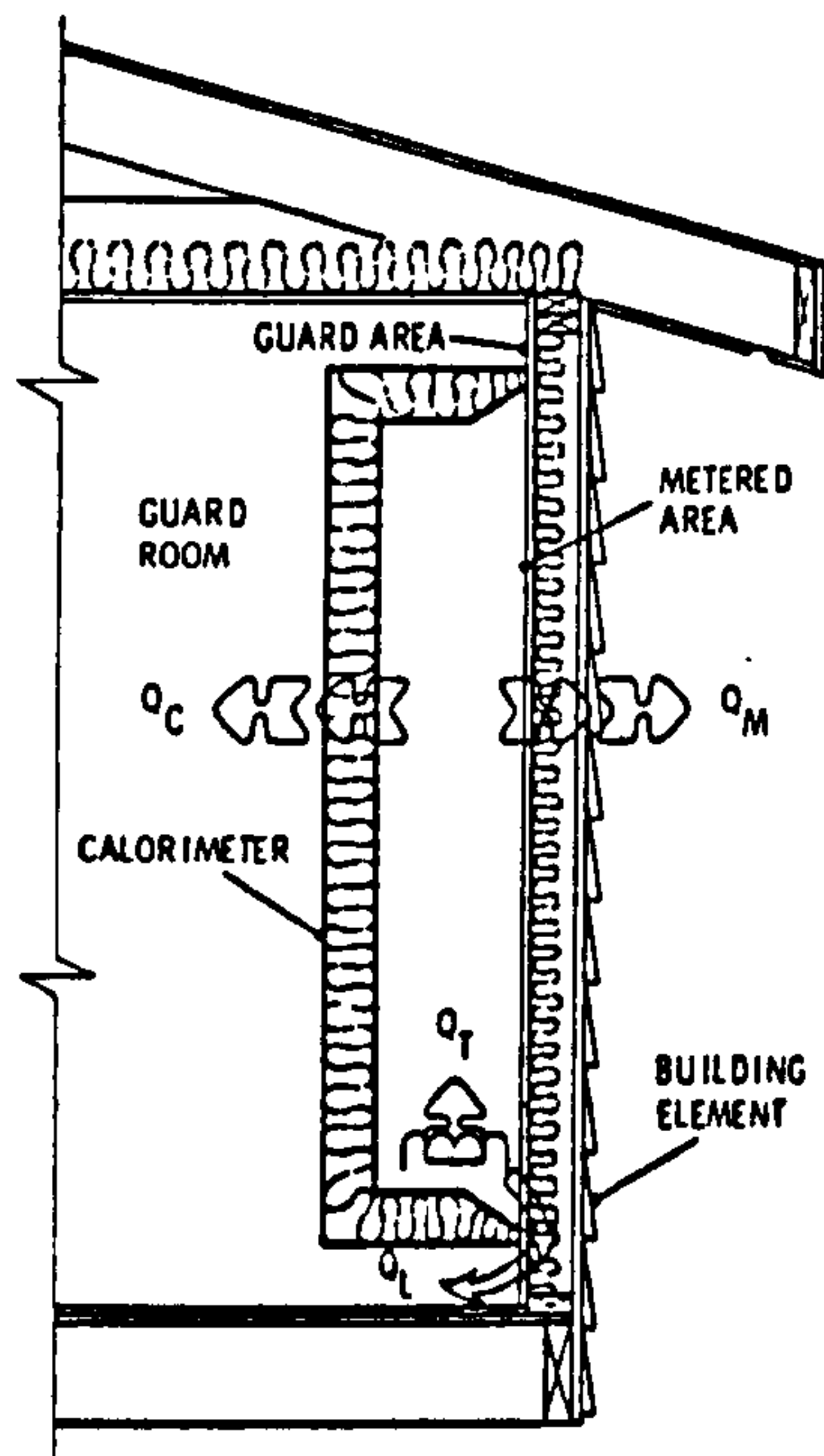
An elaborate scheme is that employed by Sherman et al (1983) at the Lawrence Berkeley Laboratories. They developed an Envelope Thermal Testing Unit (ETTU) which consists of two 1.2 by 1.2m blankets which are placed against each face of a test wall (Fig. 3.5). Each blanket contains two heating sections (electric heaters separated by a low thermal mass insulating layer) which allow the heat flux into each side of the wall to be controlled separately. Between each heater layer and the insulating layer is an array of temperature sensors used to measure the surface temperatures of the insulating layer. The blankets are also slightly flexible so that they can conform to slight irregularities in the wall surfaces. The device is portable, and the heat flows rather than the temperatures are the independent variables.

Larson (1985) describes a field testing approach which employs heat flow sensors attached to a temperature-controlled 1.22m square test plate (Fig. 3.6). The test plate is portable and is used for insitu thermal resistance measurements of building envelope components. The plate uses multiple heat flow sensors so that it can measure the heat transfer through a building component over a reasonably large area. It may be placed on top of an insulated roof system or against an insulated wall system, and thermocouples are attached to the opposite surfaces of the envelope systems. Measurements can be made without disturbing the structure of the envelope systems by using test plate temperatures approximating normal outside surface temperatures. Typically, the plate is placed against the outside surface of the building or building component, is heated or cooled to an equilibrium temperature either above or below the inner surface temperature, and the inside and outside surface temperatures and the heat flow are measured. Finally, the test plate provides constant temperature conditions on the outer surface of the building component, but there is a lack of control on the inside surface temperature.

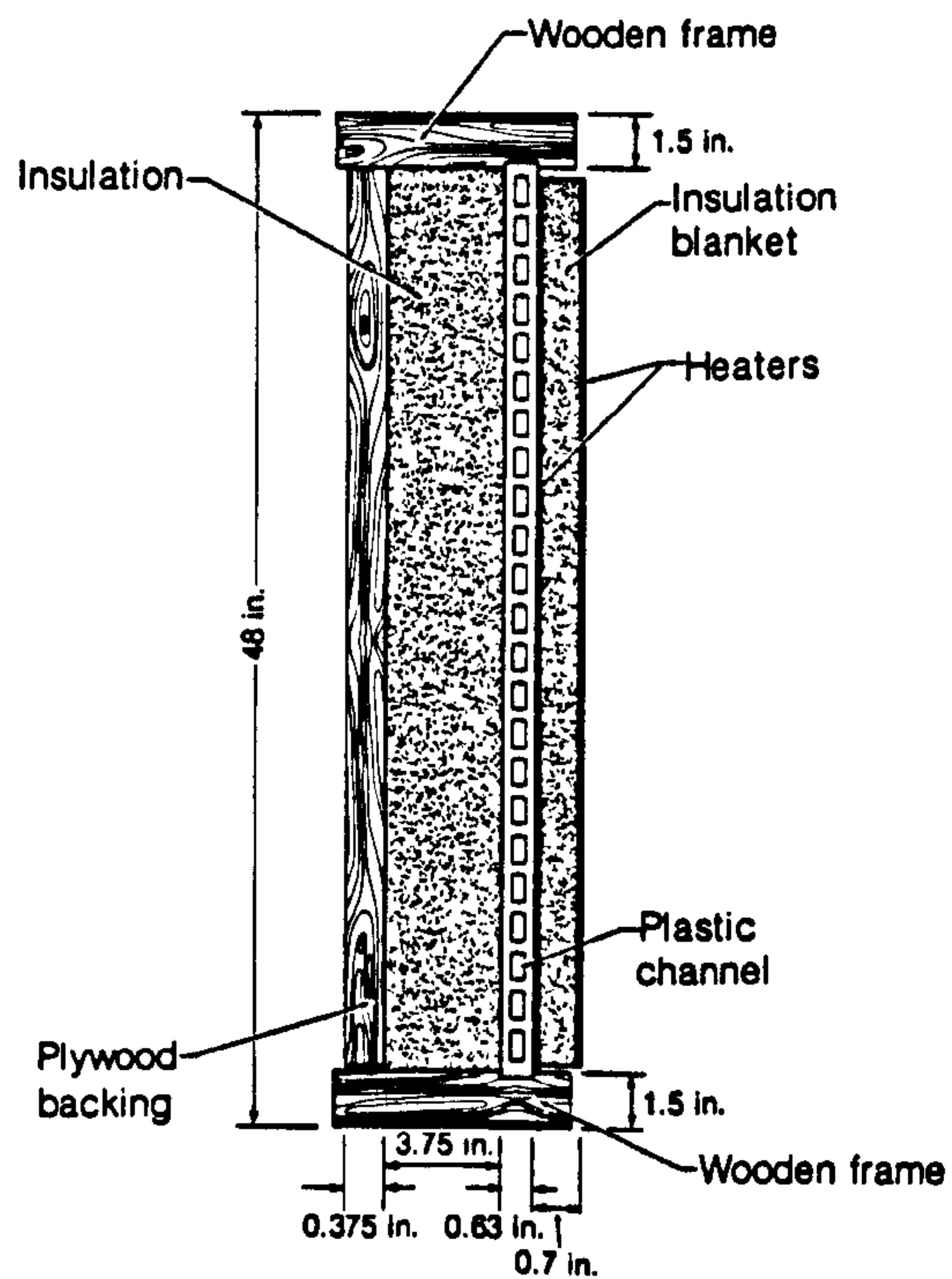
### **3.1.3 Heat flow and temperature sensors**

Laboratory and field measurements of building envelope components can be also made by attaching temperature and heat flux sensors on the inner and outer surfaces of the wall. Long term averaged heat flows and temperature differences allow average thermal transmittance values of the building components to be determined.

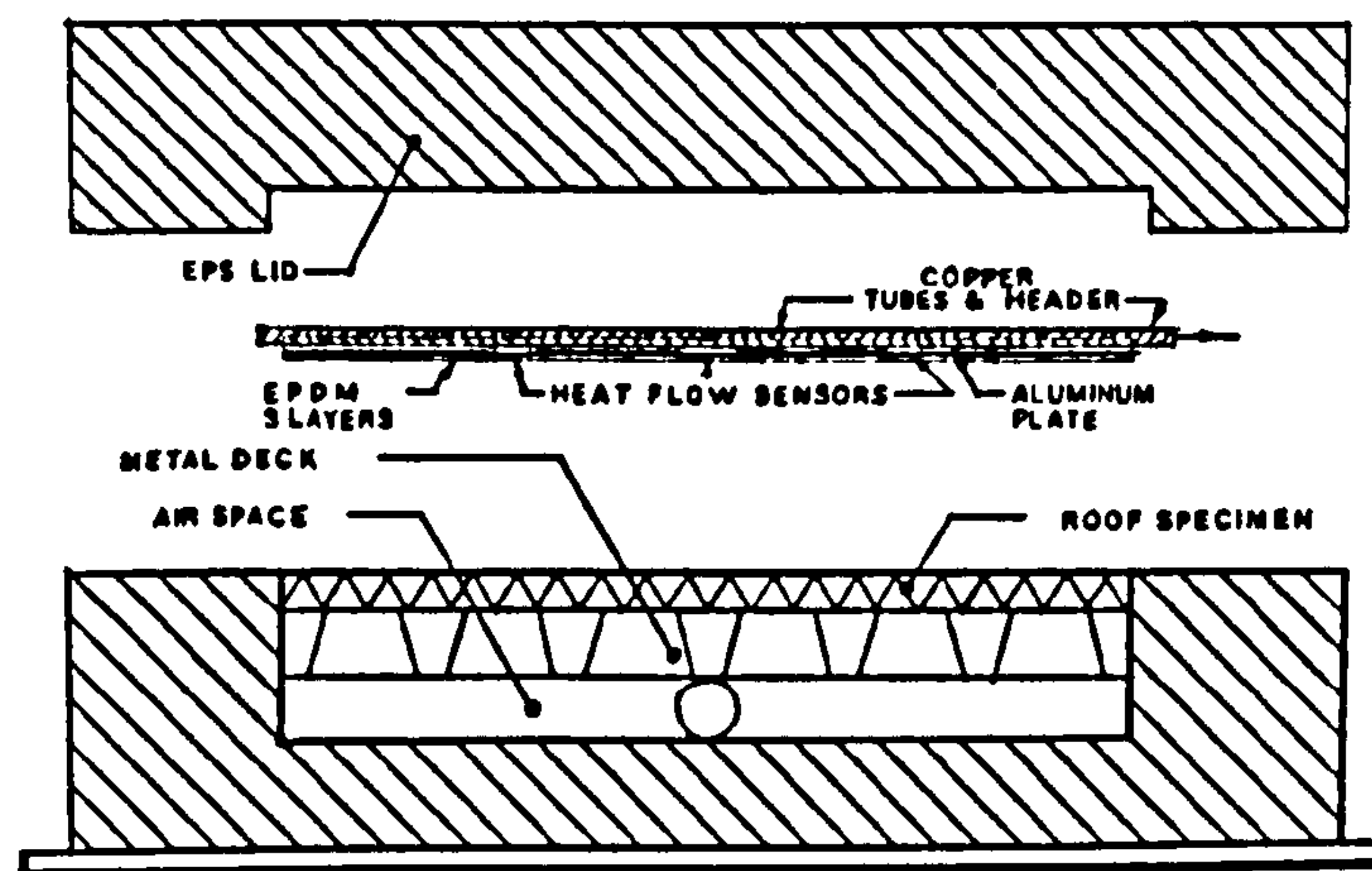
While this method has been used in the laboratory (Simpson et al. - 1988, Valentine et al. - 1989, etc.), it is also the most widely used technique for field measurements - Fig. 1.6/chapter 1, (Hedlin et al. - 1980, Treado - 1980, Anderson and Ward - 1981, Brown and Schuyler - 1982, Anderson - 1984-II, Roulet et al - 1985, Flanders - 1985, Isaacs and Trethowen - 1985).



**Fig. 3.4:**  
*Schematic of a field calorimeter*  
 (After Brown and Schuyler - 1982)



**Fig. 3.5:**  
*Cross-sectional view of the Envelope Thermal Test Unit (ETTU)*  
*blanket within its support structure* (After Modera et al - 1987)



**Fig. 3.6:**  
*Roof module test configuration*  
*(After Larson - 1985)*

This technique requires that the heat flow and the internal and the external wall surface or air temperatures are recorded at the same time. Temperatures are usually measured using thermocouples, thermistors or platinum resistance sensors/thermometers (Anderson - 1984-II).

A large number of terms exists in the literature for this particular type of sensor: heat flux transducers, heat flow plates or meters, heat transmission meters, heat flow mats, heat flow discs, etc. The term Heat Flux or Flow Sensor (HFS) is used throughout the present study.

The use of HFSs for full-scale testing of the thermal resistance of walls started in Germany at the Thermal Protection Laboratory in Munich and in the United States at the Research Laboratory of the American Society of Heating and Ventilating Engineers in Pittsburgh, Pennsylvania, [Houghten (1922), Nicholls (1924-I), Nicholls (1924-II)].

It is clear from recent literature that there still many problems with calibration and application, of these devices, as well as analysis of measurements. One of the major problems is that separate standard calibration and application practices for HFSs do not exist at a national or international level. Nevertheless, the HFS slowly gained popularity until it became an integral part of different measuring systems used to evaluate the thermal performance of buildings.



### **3.1.4 Conclusions**

In practice there are mainly two reliable methods that can be used in the field in order to establish the thermal performance of the wall: (1) the method which employs portable guarded hot boxes and (2) the method which employs HFS<sup>s</sup> and temperature sensors.

#### **Active measurement systems**

The first method is associated with the so called "active measurement systems" where fluxes are generated on the wall surface and the resulting temperature response is measured. The advantages and disadvantages of an active measurement system are as follows (based on Modera et al - 1987):

##### **Advantages**

- (1) The measurements are assumed to be independent of the weather, that is they do not rely on naturally induced fluxes or temperature differences to provide measurable results.
- (2) The desired flux/temperature frequencies and amplitudes can be specified directly.
- (3) Due to a larger test area, the average thermal performance of the wall tends to be established rather than the performance at one single point on the wall surface.
- (4) It is a non-destructive method.

##### **Disadvantages**

- (1) It is a complicated procedure, since precise control of heat fluxes or temperatures is required.
- (2) Most of the equipment used has been designed for specific research applications and consequently is not easily available commercially.
- (3) They are expensive.
- (4) They are bulky compared to HFSs.
- (5) If multiple measurements are to be performed on the same wall at the same time, the cost involved is substantial.

#### **Passive measurement system**

The second method is associated with the so called "passive measurement systems" where naturally occurring heat fluxes and surface temperatures are measured. The advantages and disadvantages of a passive measurement system are as follows (based on Modera - 1987):

## **Advantages**

- (1) The method is much simpler to apply than the portable guarded hot box, requiring one or several measuring sets (each set comprising one HFS and two temperature sensors).
- (2) The method employs equipment that is commercially available and easy to use.
- (3) Where multiple measurements are required on the same wall at the same time, the cost involved is relatively low.
- (4) It is a non-destructive method.
- (5) Entry can be gained into the building with the minimum of disturbance.
- (6) Due to the advantages above, it is the most widely used method and thus well documented (Anderson - 1984-II).

## **Disadvantages**

- (1) Measurements rely on weather conditions, in other words it is advisable to perform measurements during the winter time when the internal/external temperature difference is high (at least 10K, McIntyre - 1985).
- (2) Their use is restricted to plain flat surfaces (Anderson - 1984-II).
- (3) The measurement area is of limited proportions.
- (4) The presence of the HFS on the wall surface affects/distorts the heat flow.
- (5) There is an absence of agreed standards.

As far as the present study is concerned the overriding consideration was the need for multiple measurements over a range of existing wall construction types. Only HFSs are capable of meeting that objective at a reasonable price. Consequently, in examining the two available methods, it was decided that the most appropriate method for the needs of the present study was the method employing HFSs and temperature sensors. Since the use of HFSs requires at least a 10 K difference across the wall, measurements using these devices can only be practically carried out during the heating season.

## **3.2 The HFS measurement system**

This section reviews the components comprising a HFS measurement system, the HFSs and the temperature sensors, and methods of mounting these on the wall surface.

### **3.2.1 Heat Flux Sensors**

A Heat Flux Sensor is a device which is used to measure vector heat flow. Typically a HFS is comprised of a thin wafer of material with a known, stable thermal resistance. It operates on

the principle that a heat flow passing through the thin wafer generates a temperature difference across the material. A HFS is designed in such a way that the temperature difference remains very small, thus minimising the influence of the sensor on the heat flow to be measured.

A large number of thermocouples (thermopile), are fitted in the wafer in such a way that the "junctions" are in contact with the surfaces, measuring the temperature difference across the wafer. The voltage generated in the thermocouples is proportional to the heat flux passing through the sensor.

HFSs may be used for a wide range of applications but this study is only concerned with those used to determine heat flow through building structures. For this purpose, they may be rectangular, square or disc shaped plates and may vary in size from 20mm to 600mm. The most common size is about 100mm. The larger HFSs (400-600mm) are used with guards (Anderson - 1984-II).

Some researchers prefer to construct and calibrate their own HFSs, best suited to their needs. Others use commercially available sensors (Trethowen - 1986).

### **HFS calibration**

The voltage output of a HFS is proportional to the corresponding heat flux through the sensor. The coefficient of proportionality between the heat flux through the sensor and its output voltage is called the calibration constant and is determined by calibrating each individual sensor. The unknown heat flow is found by multiplying the voltage value by the calibration constant.

Extensive research has been carried out by a number of workers on the calibration of HFSs such as, Schwerdtfeger (1970), Johannesson (1979), Orlandi et al (1983), Trethowen (1985). In practice, HFS calibration techniques may be classified as follows:

- (1) The guarded hot plate (GHP) technique
- (2) The radiation enclosure technique
- (3) A technique that has been developed at the Massachusetts Institute of Technology (MIT) and is traceable to the US National Bureau of Standards.

For detailed descriptions of the three techniques, the reader may refer to Bligh and Apthorp (1983) and Apthorp and Bligh (1985). Most researchers have used the guarded hot plate (Trethowen - 1986), which is the technique used by Van der Graaf (1985) for the calibration of the HFSs used in the present study.



The HFSs produced by TDP TNO-TH (Institute of Physics - Delft - Netherlands) are individually calibrated by a relative method and related to an absolute calibration measurement. Newly produced HFSs are, together with one already calibrated, placed in a layer of material through which a homogeneous heat flux is generated. From the measured signals the calibration values are calculated. The HFS is then calibrated absolutely in a purposely made apparatus which is a smaller version of a guarded hot plate.

### **3.2.2 Temperature sensors**

Temperature sensors are devices with properties that change with temperature in a predictable, reproducible manner. The range of electrical temperature sensors is subdivided into two main groups, namely those requiring excitation, and those giving an output voltage without excitation. In the first group belong the resistive types, such as platinum resistance thermometers and thermistors. In the second group belong the thermocouples and thermopiles. Copper-constantan or nickel based thermocouples have generally been preferred (SERC - 1983).

Table 3.1 summarizes the accuracy, stability, advantages and disadvantages of the three most widely used temperature sensors, namely, thermocouples, thermistors and platinum resistance thermometers.

Thermistors were found to be the most suitable for the present study since there are highly accurate, consistent, commercially available, inexpensive and excellent to use with portable data logging equipment.

THERMOCOUPLES	THERMISTORS	PLATINUM RESISTANCE THERMOMETERS
<p><b>Basic Principles</b></p> <p>If a circuit is made up of two lengths of wire of dissimilar metal with one junction kept at a higher temperature than the other, a small voltage appears, driving current around the circuit. The size of this voltage and the way it changes with temperature depends on the constitution of the metals or alloys used in the wires, as well as the temperature difference.</p>	<p>This depends on the change in resistance of a semi-conductor material. Unlike the PRT, thermistors may increase or decrease their resistance with temperature depending on type, but they are usually non-linear and the rate depends very much on the composition of the semi-conductor.</p>	<p>This is the change in resistance of a length of platinum wire or an evaporated platinum film. The resistance is very low (typically 100 ohms at 0°C rising to 240 ohms at 100°C), but is a function purely of the dimensions of the resistance film, or wire, and its temperature.</p>
<p><b>Estimated Practical Accuracy</b></p> <p>0.2°C can be achieved with care including encapsulation of junctions in epoxy resin and freedom from mechanical stress.</p>	<p>0.2°C provided sensor is frequently calibrated to 0.1°C. Uncalibrated sensors can give very large errors.</p>	<p>About 0.1°C for systems with self-calibrated sensors and good stable amplification systems increasing to 0.5°C for systems with Grade 2 sensors uncalibrated and without stable amplification.</p>
<p><b>Long Term Accuracy and Stability</b></p> <p>0.2°C is achievable, provided a good stable zero reference is provided in the data logging equipment.</p>	<p>Believed to be quite good, provided a calibration and checking is carried out.</p>	<p>Stability is very good, probably better than 0.1°C per year.</p>

**Table 3.1:**  
*Advantages and disadvantages of three widely used temperature sensors*  
*[thermocouples, thermistors and platinum resistance thermometers]*  
 (After SERC - 1983)

THERMOCOUPLES	THERMISTORS	PLATINUM RESISTANCE THERMOMETERS
<p><b>Advantages</b></p> <p>These are the most inexpensive sensors once the amplification system has been bought and provided wire runs are not too great. They are very useful for measuring temperature differences using multiple junctions in series. This does not require the use of a zero reference, although the junctions should be carefully checked to ensure that there is no off-set voltage generated. They also have a very low thermal inertia and can be used for measuring rapidly changing temperatures or surface temperatures.</p>	<p>Thermistors are inexpensive and produce a high output for a low current drive. They are, therefore, excellent for use with battery equipment or in installations requiring large numbers of sensors.</p>	<p>The voltage generated is reasonably high and the device has a good reputation for reliability and accuracy.</p>
<p><b>Disadvantages</b></p> <p>The cost of the wiring required is very high because of the special purpose wire necessary, and amplification may be expensive because of the low signal level. Great care must be taken in forming the junction to be used that spurious voltages, due to stress or corrosion, are not generated.</p>	<p>Historically they have a very bad reputation for drift and require frequent calibration and checking. Excitation current must be limited to stop self heating and they are only linear over a very small temperature range so that processing will be needed of the data collected. Thermal inertia can be low provided that they do not need to be encapsulated, but if they are, then response time may be of the order of five or six minutes.</p>	<p>They have a relatively very high cost for the sensor and its associated four-core wiring. They require a high drive current which may lead to self heating and is poor for battery operated equipment. Their thermal inertia prevents them being used for rapidly changing temperatures.</p>

Table 3.1: (continued)



### **3.2.3 HFS and temperature sensor mounting methods**

HFS and temperature sensor devices can be mounted in three basic ways (Trethowen - 1985).

- |                     |  |
|---------------------|--|
| (1) Embedded        | They may be embedded within a slab of material through which the heat flux is to be determined.  |
| (2) Sandwiched      | They may be built into a portion of a large, thin layer having the same thermal properties as the sensor which is then sandwiched between other layers of the wall construction.       |
| (3) Surface mounted | They may be mounted on an available surface, with or without edge guards. The surface may be a visible surface of the test piece or an internal surface exposed to an internal cavity. |

The "embedded" method has been comprehensively examined by Philip (1961) and later Schwerdtfeger (1970) with respect to HFSs. They showed that the relative conductivities of the sensor and parent materials and the sensor dimensions are the main factors affecting reliable performance. In practice it is a destructive method. Heard and Ward (1982) embedded their sensor (using electroplated thermopile detectors) within plasterboard and the calibration technique they used was to duplicate this condition in a guarded hot plate. It is the best of the three methods, mainly because rapid temperature fluctuations or spurious fluctuations due to air movement, are absorbed by the thermal mass of surrounding material.

The "sandwiched" method is usually encountered in laboratory thermal conductance measurements. The principal aim in this case is near-homogeneity of thermal properties between the sensor and its surroundings, to preserve one dimensional heat flow. In practical terms, the method is destructive and can not be applied to existing wall constructions.

The "surface-mounted" is the most extensively used method, favoured by the majority of workers, for both field and laboratory measurements. It is the easiest method to implement with existing structures, but it is the most complex mainly because it does not give full control of the measurement process and is difficult to analyse because of the surface effects.

It is the most important method from an engineering point of view as it is often the only non-destructive available method of measuring heat flow in real buildings. The complexity arises because the disturbing factors cannot be designed out (as in the case of the first two methods) but instead, have to be controlled and assessed.

Various techniques for attaching HFSs to the wall surface exist, including pressure, glue or grease, adhesive tape, Bluetac and Vaseline. Five methods of mounting on the surface of smooth plaster were tested by Siviour and McIntyre (1982), with the results shown in Table 3.2, expressing the measured heat flow as a percentage of that measured using the greased sensing head.

Method of application		Relative heat flow (%)
(1)	Thin layer of silicone grease between sensor and wall	100
(2)	Dry sensor taped to wall	98
(3)	Sensor bedded in thin layer of silicone putty (e.g. Bluetac)	98
(4)	Double-sided adhesive tape	89
(5)	Sensor pressed against wall by low conductivity rod	83

**Table 3.2:**  
*Relative effectiveness of application methods.*  
*Sensor was applied to smooth plaster surface.*  
*(After Siviour and McIntyre - 1982)*

While this suggests that the layer of silicone grease is adequate to ensure good thermal contact, there is a systematic error due to the fact that the silicone grease used as a medium between the sensor and the wall surface had a finite contact resistance.

**3.3 Field measurements**

Since a wall is subject to normal diurnal temperature variation, steady state conditions are impossible to achieve, and errors will be introduced because part of the measured heat flux may be contributing to a change in the temperature of the wall rather than to simple conductive heat flow. This has considerable implications for the accuracy and reliability of thermal transmittance measurements.

In this section a brief review is presented of the errors involved in field measurements and the precautions taken to minimize them (i.e. favourable measurement conditions). A detailed error analysis in the context of the actual system used is presented in chapter 5.

### **3.3.1 Errors involved in field measurements when using a HFS measurement system**

Where field measurements are concerned, it is necessary to record heat flux and temperature gradient over a period of days, so that the effects of the heat storage in the wall on the resulting thermal transmittance value may be minimised i.e. the net flux through the wall is measured. Errors may also be introduced because of the effects of the environmental conditions on the basic thermal properties of materials such as moisture, air velocity and air infiltration effects. Complex heat flow patterns at interfaces of different materials may exist e.g. thermal bridges, there may be possible differences between the design and the structure as built, interference of monitoring equipment. The errors introduced in the measurements should not be disregarded, but taken into account and assessed.

The use of a HFS is complicated by several factors. For example, adding the sensor to a wall changes the local resistance and causes the local heat flow to differ from that for the undisturbed wall. In addition, since the resistance of the sensor generally differs from that of its immediate surroundings, the heat flow in this region is not one dimensional, which changes the calibration of the device.

The experience of different workers in the field indicates that accuracy is attainable within a 5% error in laboratory applications and within the range of 5 to 20% for insitu applications for the careful user (ASTM - STP 822, 1985). For example, Grot (1982) cited overall accuracies of  $\pm 6\%$  in the field, Brown and Schuyler (1982) concluded that ".....reasonably accurate ( $\pm 10\%$ ) values of insitu frame wall thermal resistance .....", Flanders (1985) discussed errors and the fact that his measured results agreed within  $\pm 10\%$  with the ASHRAE calculations, Isaacs and Trethowen (1985) investigated the R-values (the reciprocal of the  $\Lambda$  value) of a large number of houses with an overall accuracy of  $\pm 10\%$ .

A number of workers attempted to investigate the errors involved in the field measurements, so that a better understanding of the causes could be achieved. For example:

Roulet et al. (1985) carried out a large scale survey insitu. He emphasizes the fact that "statistical errors may occur due to slight variations in the thermal contact between the sensors and the surface or by small local temperature perturbations in the vicinity of the HFSs". To determine the importance of this effect, they carried out a laboratory experiment using 14 HFSs placed on a wall surface and signals were recorded from time to time. Between these measurements, the position of some of the HFSs were changed on the wall or



were simply taken out and installed again, to simulate a new start of a measurement. More than 100 measurements were made this way. The dispersion of the measurements as taken, was quite large, about  $\pm 20\%$  of the average value. They conclude that:

- (1) This experiment shows that the uncontrollable statistical errors for a heat flow measurement on a building element is about 5% of the mean value.
- (2) In order to obtain precise results, several HFSs must be installed at various locations.

Field use errors of the order of 100% are not unusual if attention is not paid to the proper technique (ASTM - STP 822, 1985). For example, Fang and Grot (1987) reported on a survey of various sections of building envelopes using both HFS and portable calorimeters. They concluded that the measured wall resistance values deviated from the predicted values by an average of 22%, with the most unfavourable circumstance being 71%.

## **Conclusions**

It is clear from the literature, that the errors occurring in the field measurements are attributed to: boundary conditions, equipment calibration, heat flow distortion resulting from the presence of the HFS on the wall surface, etc.

Emphasis must be given to the following three issues:

- (1) A number of HFSs must be installed on the wall surface so that the average performance of the wall can be established. During the measurement, the HFSs must be taken out and installed again on the same or different positions on the wall in order to establish the differences between the sensors themselves and that due to the different positions on the wall surface.

The latter point is emphasized by Flanders (1985) who mentions that: ".....R-values indicate that much of what may pass for HFS error may actually be variation in building performance". With changing the sensors around, the variability in the performance of the wall due to factors such as workmanship and material properties can be established. It must however be noted that changing HFSs will mean that calibration and fixing errors must also be taken into account.

- (2) In order to reduce the uncertainties involved in the field measurements within the range of  $\pm 5\%$  to  $\pm 10\%$ , great care must be taken during the installation of the equipment and the measurement has to be carried out under carefully controlled conditions.

(3) The errors involved must be evaluated in the context of the system used, i.e. the figures quoted above are only valid for a particular set of circumstances.

### **3.3.2 Recommended conditions for field measurements**

A literature review follows on recommended conditions for field measurements, by previous workers.

Flanders and Marshall (1982), carried out a series of measurements on a West-facing masonry cavity wall with the following findings:

- (1) The temperature difference is the most significant variable causing the data to converge rapidly on a steady cumulative value for thermal resistance.
- (2) The difference between using the guard in the HFSs and not using it was about 13% for the larger HFSs, which had built-in guard areas, and 7% for the smaller ones.

McIntyre (1985) reported on a series of experimental measurements in test houses and discussed the practical aspects of measurement such as, room heating, sensor mounting, temperature measurement where he recommends that wall surface temperatures be measured, rather than the inside and outside air temperatures and concludes with conditions for successful measurement (outlined below) and that ".....reliable estimates of U value can only be obtained from readings extending over a period of a few days". In his "conditions for successful measurement", McIntyre suggests that the "minimum" conditions for U value measurement are:

- (1) A room that has been heated for three days previous to the measurement.
- (2) A recording period of 24 hours.
- (3) An inside/outside temperature difference of 10K.
- (4) A number of measurements must be made on the same wall at the same time, since "a single point measure of U value, however accurate, is of limited value unless it can be related to the wall structure as a whole".

He advises that where measurements do not meet the above minimum conditions "should be disregarded". Indeed he further recommends the following set of desirable conditions:

- (1) Continuous, steady internal heating.
- (2) A room that has been heated for three days.
- (3) A recording period of two days or more.
- (4) An inside/outside temperature difference of 15K or more.

- (5) Thermal imaging for determination of HFS positions.
- (6) A thin layer of silicone grease must be applied between the sensor and the wall surface for better thermal contact.
- (7) Cloudy, stable weather conditions.
- (8) North facing wall.
- (9) Outer surface temperature measurement opposite HFS.
- (10) The recommended minimum monitoring period for a heavyweight wall is 8 days.

Flanders (1985) reported on R-value measurements of 20 buildings at four Army bases. He addresses the validity of using surface-mounted HFSs on walls to determine thermal characteristics and he employed the following guide-lines for his measurements.

- (1) Infrared thermography was employed for the detection of building defects.
- (2) Wall surface temperatures were recorded rather than air temperatures.
- (3) A number of HFSs were installed on the same wall surface.
- (4) The guard area of the HFS had the same conductivity as the sensing area.
- (5) Masking tape was used to attach the HFSs on the wall surface for two reasons: to match the absorptivity of the sensor to its surroundings and to smooth the flow of air. Subsequent inspection with a radiometer to indicate whether the match of absorptivity between sensor covering and sensor surroundings was close, was also applied.
- (6) Gel toothpaste was applied as the medium between the HFS and the wall surface in order to increase thermal contact.
- (7) The frequency of measurement for every sensor was 40 seconds to ensure integration of the heat flux.

Roulet et al (1985), carried out an extensive survey of HFS field measurements on 9 building elements (from very light to very heavy), in Switzerland, over times ranging from 6 hours to up to 50 days. They found that:

- (1) For very light elements, data taken over short periods of measurements (6 to 12 hours), give good results, if solar radiation is avoided i.e. one night is long enough to give reliable results.
- (2) For heavier elements, if the indoor temperature is constant before and during the measurement, the data give stable results in the same measurement time.
- (3) As far as the influence of the indoor/outdoor temperature difference is concerned, the smaller the average temperature difference, the longer the necessary duration of measurement.

A code of practice for such measurements was also written. Recommended intervals and measurement times are listed in Table 3.3.



Trethowen (1985) suggested that "(a) HFS devices should never be directly exposed to sunshine but should be concealed below a sample of the parent surface and that (b) flux measurements for R-value determination should be made on the inside wall surface only."

Isaacs and Trethowen (1985) conducted a large scale survey in which roof, wall and floor insulation R-values were measured insitu in 63 occupied houses during winter time. They measured surface to surface R-values and they also mention that: ".....at least three or four days recording are needed" for timber framed structures, however, much longer is needed for continuous concrete perimeter foundation walls since the thermal capacity is larger. The typical monitoring period for their measurements was approximately 72 hrs.

Element type	Interval (mins)	Time (hrs)
Light elements	5 to 15	6 to 12 (night)
Heavy elements (stable indoor temperature)	15 to 30	12 to 96
Heavy elements (unstable indoor temperature)	30 to 60	480 to 1200
<p><b>Table 3.3:</b>  <i>Recommended recording intervals and measurement times for insitu U value measurements.</i>  <i>(After Roulet et al - 1985)</i></p>		

Modera et al (1985) carried out field measurements of U value. They attempted to quantify the errors associated with data interpretation. They concluded that ".....our analysis has shown that instantaneous field measurements of surface temperatures and heat flux cannot provide accurate estimates of the U value of a wall". Their analysis also indicated that the "accuracy of wall U value estimations can be significantly improved if time-integrated temperatures and fluxes are used". They provided the following example, ".....it appears that a 6-h measurement of temperatures and fluxes is adequate to measure the U value of an insulated cavity wall within about 10% error, provided that the following are true:

- (a) the indoor-outdoor temperature difference is at least 20K,
- (b) the daily outdoor temperature swing (high to low) is not larger than half the average indoor-outdoor temperature difference, and
- (c) the average indoor and average outdoor temperatures do not vary significantly over the course of the test".

However, they also mention that for masonry walls the required measurement time is considerably longer under the same test conditions.

### **3.3.3 Best current practice**

A summary of the conditions recommended from previous workers quoted above in obtaining successful field measurements (accuracy range between +/-5% to +/-10%), which should be applied are as follows:

- (1) The room where the measurements are to be carried out should be heated for three days prior to the commencement of the measurement.
- (2) For heavyweight elements, a recording period of not less than 96 hours should be applied.
- (3) Wall surface temperatures rather than air temperatures should be recorded.
- (4) An internal/external minimum temperature difference of 10K should be applied where possible.
- (5) Thermal imaging for HFS placement is to be exercised prior to the installation of the sensors on the wall surface to avoid thermal abnormalities.
- (6) A thin layer of thermal paste must be applied between the sensors and the wall surface for better thermal contact.
- (7) Continuous, steady internal heating, should be applied if possible, in order to minimize the length of the measurement period.
- (8) The sensors should be attached on a north facing wall in order to minimize the influence of the solar radiation.
- (9) The external surface temperature measurement should take place opposite the HFS.
- (10) A number of HFSs should be installed on the same wall surface following the practice of Roulet et al (1985) and Flanders (1985).
- (11) Masking tape should be used, (matching absorptivity with the wall surface, where possible) to attach the HFS on the wall surface.

It should be emphasized that this section was only an introduction to the field measurements, the errors involved and the best current practice available to perform such a measurement. A detailed analysis of the errors involved in the field measurements of the present study with the actual system used is given in chapter 5. However it is considered

most appropriate that the experimental technique adopted in the present study is presented in the next section.

3.3.4 Field measurements as performed in the present study

Experimental technique

The experimental technique adopted during monitoring is presented below.

Equipment used

The measurements were carried out using circular TPD TNO-TH (Institute of Applied Physics-Delft-Netherlands) HFSs of the PU 4.3 type. The sensor is a thermopile of 100mm. diameter, 3mm thick with an active area of 30\*30mm. The remaining part of the material is used as a guard around the sensitive area to try to maintain a perpendicular heat flow into the wall area adjacent to the sensor. Each HFS is supplied with its individual certificate which records its characteristic information. An example is given below:

---

Heat Flux Sensor type	PU	4.3
Serial Number	PU 4.3	0067
Calibration Value C (at 20 °C)	5.9	(W/m <sup>2</sup> mv)
Temperature Correction	+0.04	(%/K)
Internal Electrical Resistance	1520	(Ohm)
Thermal Conductivity	0.25	(W/mK)
Accuracy of Calibration Value	+/-5	(%)
Maximum Temperature	90	(°C)
Stability	Highly stable for at least 4 years	

---

Heat Flow (W/m<sup>2</sup>) = C \* measured voltage (mv)

---

The temperature sensors used were precision mini-thermistors of the type UU supplied by Y.S.I., Yellow Springs, Ohio, USA (Grant - 1987). They can be used over a range of -50 °C to +150 °C. Every thermistor is individually calibrated with instruments traceable to U.S. National Standards. They have a resistance of 2000 Ohms at 25 °C.



Infrared thermography, using an AGA thermovision 782 system (Agema - 1984) facilitated the placement of HFSs to avoid thermal abnormalities due to structure or defects, such as cold bridges, edge effects, etc. Thermograms were obtained from the video-taped recordings for all walls investigated (thermographic equipment can be seen in Plate 3.1 and a typical thermogram is shown in Plate 3.2).

#### **Procedure adopted**

Care was taken to ensure that all sensors were at least 200mm from the edge of the windows or wall corners in order to minimize edge effects or cold bridges (Dudek - 1987). Even with this precaution, some of the measurements exhibited discrepancies which have been attributed to edge effects.

It was decided from the outset of the project that the procedure to be followed in the field measurements, had to be compatible with the BRE guide-lines. While several methods of mounting the HFS are available (Siviour and McIntyre - 1982), the most appropriate method in the circumstances was to attach the HFSs and thermistors to the wall surface using a layer of silicone grease, in order to reduce the contact resistance. The edges were covered with masking tape, so that the sensors would remain attached on the wall surface during the period of measurement and the flow of air over the sensors would be reasonably smooth.

Measuring sets had to be assembled and unique numbers or letters allocated for each set. A set comprised one HFS and two mini-thermistors, recording inside/outside wall surface temperature, which were always kept together (details in chapter 5).

The internal and external wall surface temperatures were measured by means of two mini-thermistors placed at approximately opposite locations, with the inside thermistor placed beside the HFS. The point where the thermistor was placed on the external brick surface was smoothed out to improve contact.

A typical installation comprised one HFS and two mini-thermistors and where space was available, three or more HFSs and the corresponding thermistors were used, preferably above and below the horizontal centre line of the wall (Plates 3.3 and 3.4). Monitoring time ranged between nine and approximately forty days, depending on the availability of the location. From each combination, heat flow and inside and outside surface temperatures were recorded using a micro-data logger (Squirrel), (Plate 3.5). North facing walls were chosen for all the measurements to reduce the influence of solar radiation.

The recording interval was set to be 15 minutes for every site. Every recorded value is an average of 300 readings taken at a 3 second interval (details in chapter 5). The data were downloaded from the Squirrels to a Compaq portable computer for storage on to floppy disks and subsequent analysis.

#### **Data transfer**

Data is transmitted from Squirrel to the computer in blocks of 255 bytes, containing 168 12 bit numbers (252 bytes) followed by a 2 12 bit number (3 byte) checksum. Each pair of 12 bit numbers is transmitted as a triplet of 8 bit bytes, giving 84 triplets followed by a 1 triplet checksum.

Each run has a header which starts at the beginning of a block. Headers, which are of variable length, are immediately followed by their associated readings in time order. An end of run character is inserted at the end of each run, with an end of recording character inserted at the end of the last run. Remaining portions of blocks are filled with filler characters. Variables have a restricted range to enable dedicated, out of range characters to be used as identifiers.

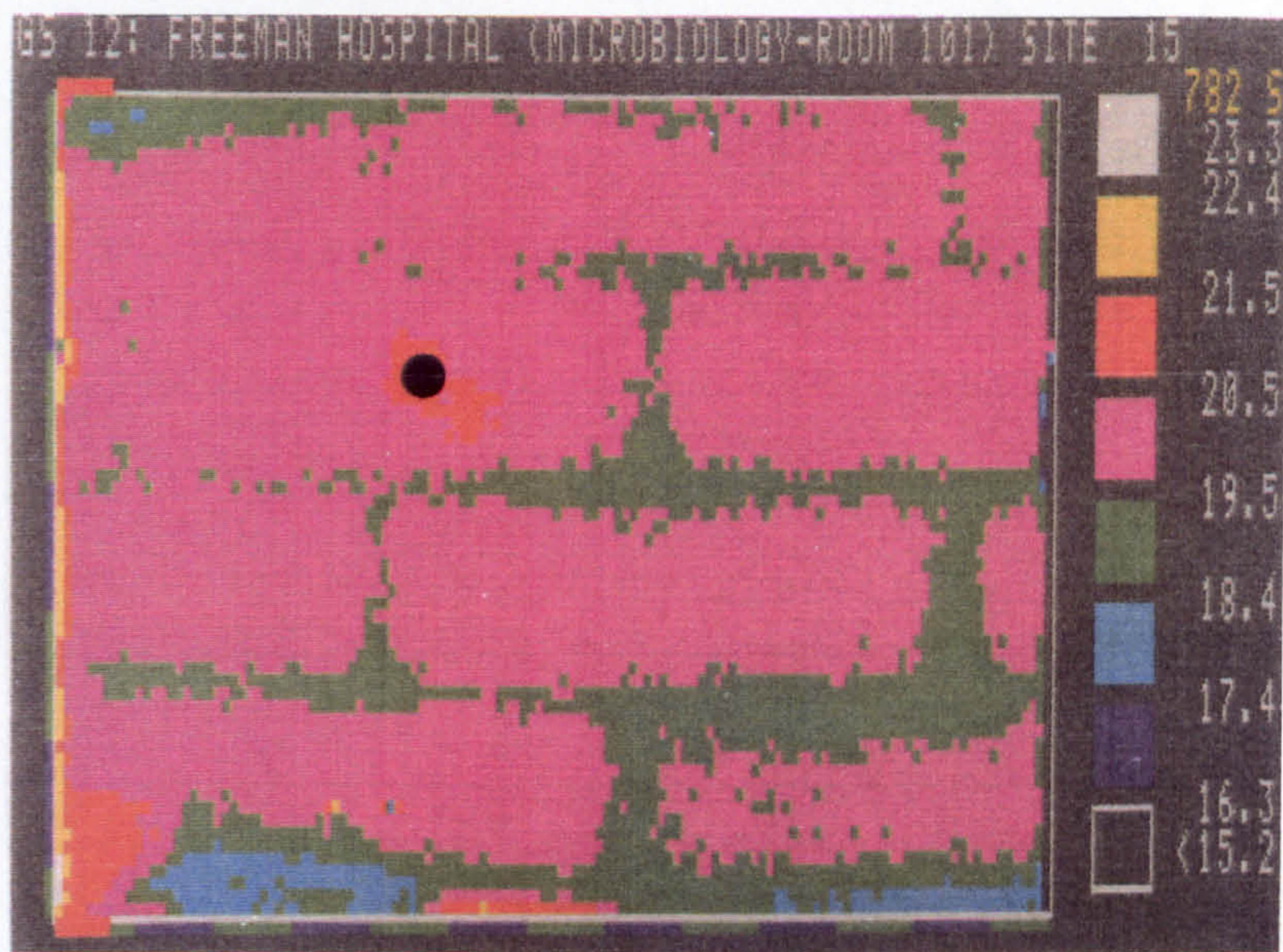




**Plate 3.1:**

*Equipment used for the thermographic inspection of a wall prior to the installation of the HFSs and mini-thermistors.*





*Plate 3.2:*

*Thermogram indicating that temperatures are analysed between 16.3 and 22.4 °C*

*The thermogram is typical of those used to determine the best position for placing the sensors. This particular example illustrates the inner leaf of an aerated block wall and clearly show the mortar joints behind the plaster. The black dot indicates the position where the HFS was placed.*





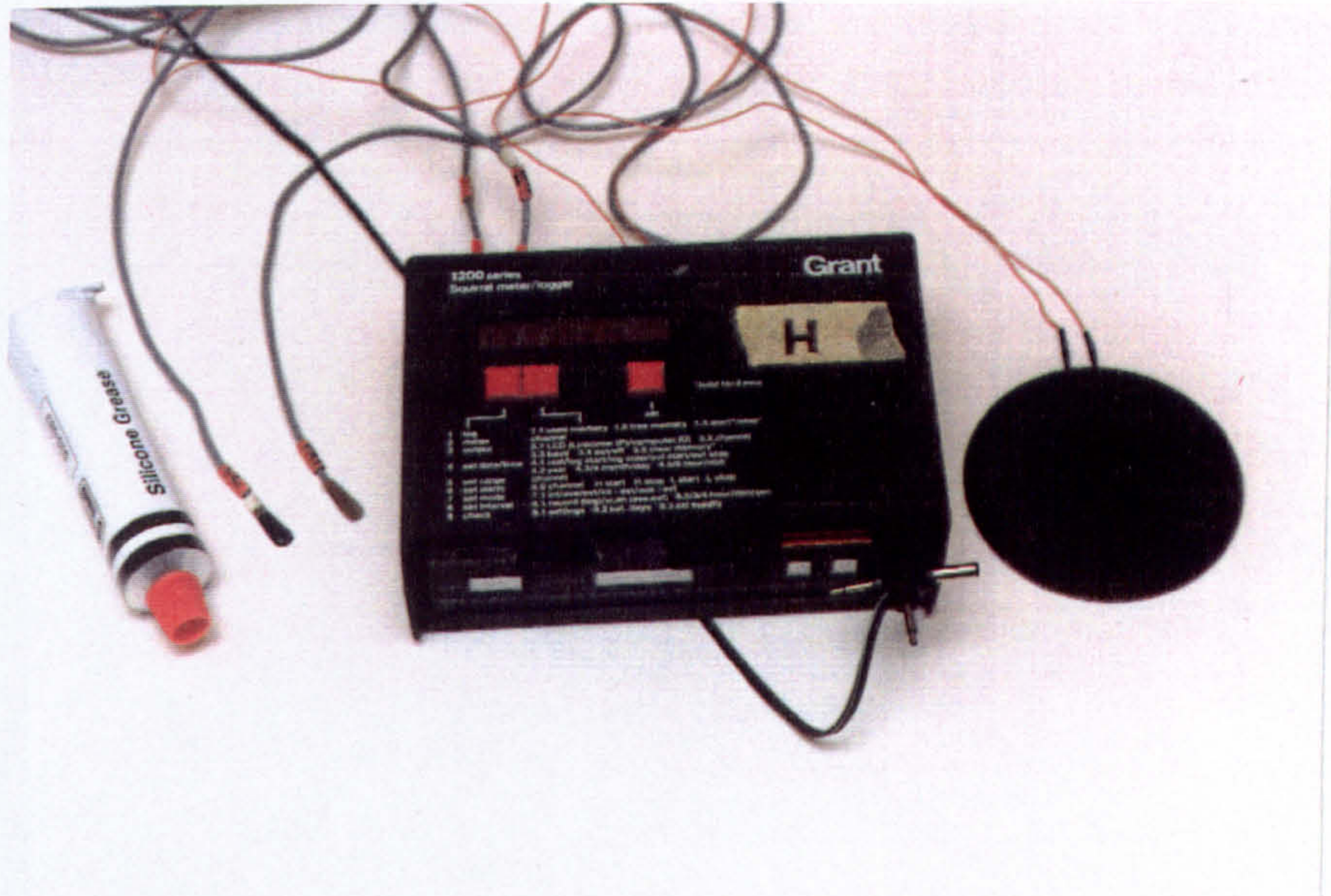
*A typical installation on the wall including 3 HFSs and 6 mini-thermistors*  
*The measuring sets are located at positions A, B and C.*



*Upper Plate 3.3:*  
*Internal surface of the wall*

*Lower Plate 3.4:*  
*External surface of the wall*





**Plate 3.5:**

**Equipment used in the gathering of thermal transmittance data**

- (1) A TNO HFS of the PU 4.3 type, used to record the heat flow through the wall fabric.
- (2) A Grant micro-data logger (Squirrel), 1200 series (13 input channels) used to record heat flow, internal and external surface temperatures.
- (3) Two Grant mini-thermistors of EU-UU type used to record the internal and external surface temperatures of the wall.
- (4) Silicone grease. A thin layer is applied on the HFS in order to reduce the contact resistance.



**PREDICTION  
OF THE  
WALL PERFORMANCE**

**CHAPTER 4**

## **4.0 Introduction**

This chapter sets out to investigate the models used to calculate the thermal transmittance value of wall constructions which are adopted as standard calculation methods by the industry, as well as more sophisticated 3D models.

In order to calculate the thermal transmittance through the wall, one, two and three dimensional (1D, 2D and 3D) models of various degrees of sophistication can be employed.

The 1D models which are basically manual techniques and are widely used at the design stage include: the basic model which assumes homogeneous construction, the area weighted model which can be used to take into account non-homogeneous construction such as the cold bridging of mortar joints (CIBSE Guide - Section A3, 1986) and both the combined (CIBSE Guide - Section A3, 1986) and the Anderson (Anderson - 1981-II) models for the more complex situations of slotted blocks.

The 2D models are generally computer based techniques and are now being superseded by more powerful 3D computer packages where a much more accurate representation of the heat flow through building elements is possible.

The calculated thermal transmittance value of any construction is usually presented as a specific value. However, in reality, this is not the case, since it is a function of both the assumptions used in the mathematical model and the data values that the model uses. For any particular set of practical circumstances the calculated value of thermal transmittance is always accompanied by uncertainty. The principal sources of uncertainty involved are:

(1) the model used to compute the value

- (i) the model may be inappropriate (e.g. use of a 1D model for a particular case, while a 3D model should be used).
- (ii) uncertainties in the input parameters for the model (e.g. boundary conditions in the cavity)

(2) the tolerance in building components and the manufacturers data values

- (i) the physical dimensions of the building components
- (ii) the thermal properties of the building materials used

In this chapter, items (1) and (2) above are discussed in order.

### 4.1 The One - Dimensional (1D), steady state model

The 1D model is a standard calculation used extensively by the industry and is recommended by the CIBSE Guide, Section A3 (CIBSE - 1986). The 1D model assumes that the wall is a plane element and ignores the effects of corners, edges and other junctions between the external envelope and the internal structural elements. The 1D model has three main variations, the basic, the area weighted and slotted block models which are examined in turn.

#### 4.1.1 The basic model

The first variation concerns the procedure based on a thermal conductance ( $\Lambda$  value) which has been calculated with a knowledge of the material thermal conductivities and physical dimensions assuming homogeneous construction and uni-directional heat flow. The basic model involves the calculation of an overall thermal transmittance value from the layers the wall consists of. The thermal resistance values for each layer of the wall are required for the calculation. These are calculated from a knowledge of the thickness of the layer and the thermal conductivity of the layer material (aerated block, brick, etc.).

$$\Lambda = \frac{1}{R_1 + R_2 + \dots + R_a} \tag{4.1}$$

where

$\Lambda$  = thermal conductance (W/m<sup>2</sup>K)

$R_1, R_2$  = thermal resistances of the construction layers (m<sup>2</sup>K/W)  
where  $R_1$  = thickness /conductivity =  $l_1/\lambda_1$

$R_a$  = cavity airspace resistance (m<sup>2</sup>K/W)

The uncertainties involved in this model are related to the thickness and conductivity values (which are discussed in section 4.4 of the present chapter) and the simplified treatment of the resistance of the cavity airspace which is discussed in the following paragraphs.

The CIBSE Guide - Section A3, recommends that airspaces can be treated as media with thermal resistance. The justification offered is that the radiation and convection heat transfer across them is approximately proportional to the difference between the temperatures of the boundary surfaces. The thermal resistance of a vertical airspace depends on factors such as,



surface emissivity, dimensions, temperature difference, effect of airspace ventilation (CIBSE Guide - Section A3, 1986).

Tabulated values for various types of unventilated airspaces in buildings are given in Tables A3.7 and A3.8 - Section A3 in the CIBSE Guide. The standard thermal resistance values for unventilated vertical airspaces which are recommended for a cavity thickness of 25mm or more are 0.180 and 0.350 ( $\text{m}^2\text{K/W}$ ) for high and low surface emissivities respectively (CIBSE - 1986).

Although the above values are included in the values given in the Guide, there is no discussion as to the validity of the values, and this may very well be a source of uncertainty for the estimation of a wall's final transmittance value.

### **Applicability of the model**

The extent to which this calculation is valid depends primarily on the assumption of 1D heat flow. This assumption is most frequently invalid where discontinuities due to the presence of dissimilar materials occur, thermal bridges are formed and the uni-directional heat flow is disturbed.

Examples are: discrete bridges such as mortar joints, solid lintels and concrete beams, multi-webbed bridges such as the bridges which occur in slotted blocks and perforated bricks and finned element bridges such as the bridges which are formed at the junction of walls and floors (CIBSE - 1986).

There are also two other factors that have to be considered:

- (1) The thermal resistance of the cavity airspace may be wrongly estimated due to differences in the assumed emissivity of the surfaces and due to the cavity being assumed to be unventilated i.e. no airflow. In practice, however, it is highly unlikely that the cavity is totally unventilated e.g. weep holes.
- (2) The value of the thermal resistance is assumed to be constant, whereas under dynamic conditions the temperature difference across the cavity airspace is not constant and therefore the thermal resistance value is variable.

Some estimate of the uncertainty introduced in the thermal resistance value of a cavity airspace due to the surface emissivity and the temperature difference across the cavity is provided in the following paragraphs.

Sharples and Page (1979), following a review of previous work developed a composite model for calculating the heat transfer across air cavities in buildings. The model applies to parallel sided air cavities within a construction which can have any inclination and any direction of the heat flow. However, a fundamental limitation of this work is that it only treats the convective component. Anderson (1981-I), proposed a more complete model which takes into account the convective and radiative components.

For horizontal heat flow in a rectangular airspace whose dimensions are  $\alpha$  in the heat flow direction and  $\alpha'$  in the other horizontal direction, where  $\alpha$  and  $\alpha'$  may be of comparable magnitude, Anderson (1981) proposed that the thermal resistance (R) of a large cavity ( $\alpha/\alpha' \rightarrow 0$ ) is given by:

$$R = \frac{1}{h'_c + 1/2 E h_r (1 + \sqrt{1 + \alpha^2/\alpha'^2} - \alpha/\alpha')} \quad (4.2)$$

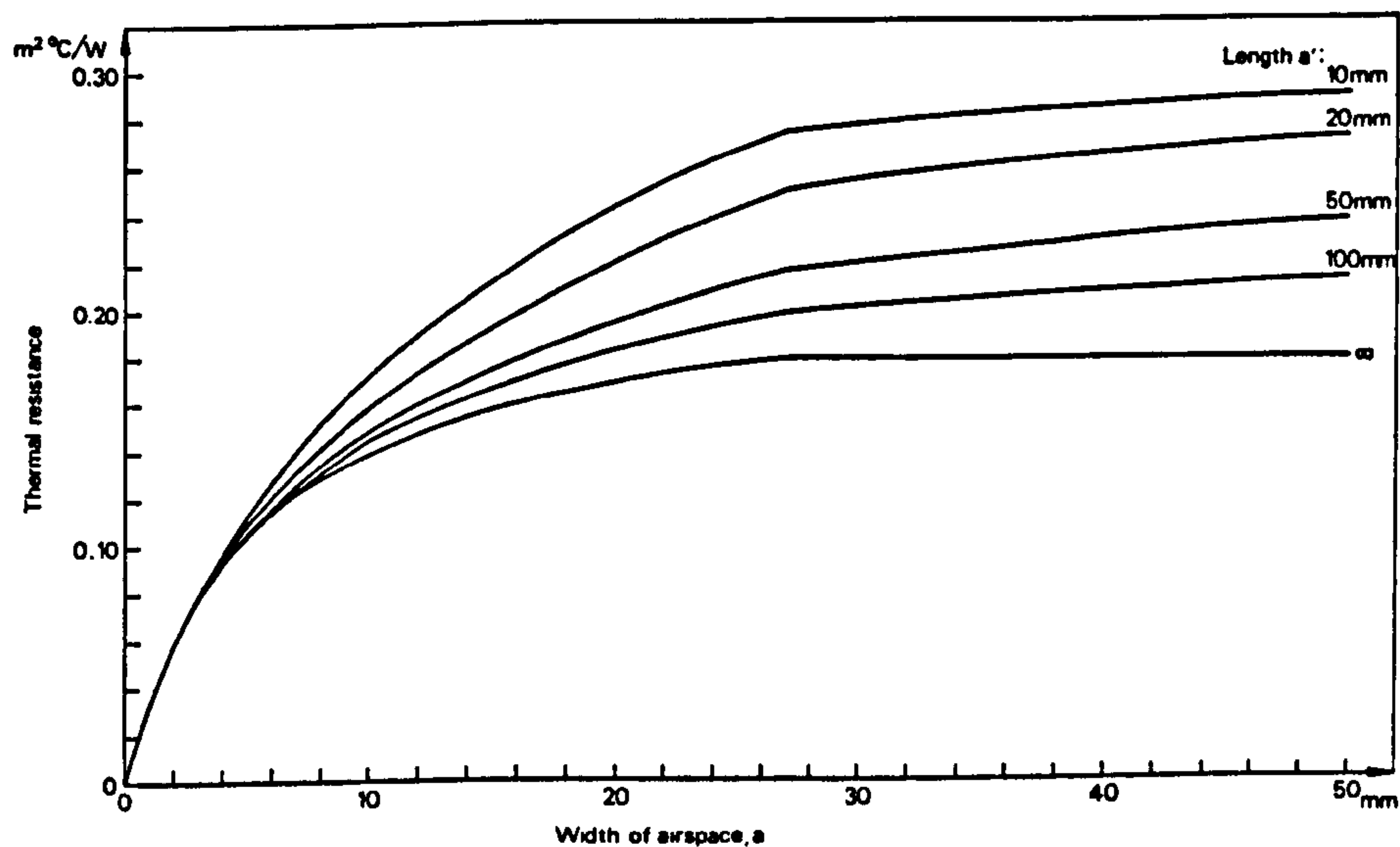
where

- $h'_c$  is the "max" of the values given by:  $[\lambda/\alpha, 0.73 (\Delta T)^{1/3}]$
- "max" = meaning that  $h'_c$  is the larger of the two expressions
- $\lambda$  = conductivity of the air = 0.025 W/mK
- $\Delta T$  = temperature difference in a cavity
- $E h_r$  = radiation coefficient ( $E h_r \sim 4.63$  at 10 °C mean temperature of the wall)
- $h'_c$  = convection coefficient ( $h'_c \gtrsim 1.0$  at 10 °C mean temperature of the wall)

However, the above model is only an approximation since in "real" building geometries it does not take into account the height of the cavity, in other words the same result is given for walls of different height.

Fig. 4.1 shows R as a function of  $\alpha$  for different values of  $\alpha'$  at a mean temperature of 10 °C ( $E h_r = 4.63$ ). It indicates clearly that for most walls (length  $\alpha' > 100$ mm and for a width of airspace  $> 27$ mm), the thermal resistance value of an airspace cavity is approximately 0.180 m<sup>2</sup>K/W, the value cited in the CIBSE Guide.





**Fig. 4.1:**  
*The thermal resistance of an airspace (horizontal heat flow) as a function of width  $\alpha$  and length  $\alpha'$  from the expression given in Eq. 4.2. (The slight discontinuity at  $\alpha = 27\text{mm}$  is a consequence of neglecting convection for  $\alpha < 27$  and assuming constant  $h'_c$  for  $a > 27$ ). (After Anderson - 1981-I)*

In exploring Eq. 4.2 in the context of a range of emissivities expected for typical wall constructions and the temperature differences that might exist across a standard 50mm cavity, appropriate values may be substituted and Table 4.1 results.

Airspace Cavity Temperature Difference $T$ (K)	Emissivity Factor $E$ ( $F_{12}e_1e_2$ )	Thermal Resistance Value ( $\text{m}^2\text{K/W}$ )
3.60	0.85	0.182
3.60	0.90	0.174
3.60	0.95	0.167
2.00	0.85	0.189
2.00	0.90	0.180
2.00	0.95	0.172
0.10	0.85	0.205
0.10	0.90	0.195
0.10	0.95	0.186

**Table 4.1:**  
*Thermal resistance values for a range of emissivities of a 50mm airspace cavity for a wall construction of  $\Lambda$  value = 1.00 (Based on Anderson - 1981-I)*

In Table 4.1 the values of 3.6 K and 0.10 K are the maximum and minimum temperature differences in the cavity corresponding to temperature differences of 20 °C and 1 °C across the wall respectively, for a given form of wall construction - in this case for a wall of  $\Lambda = 1.0 \text{ W/m}^2\text{K}$  - (Anderson - 1981-I). If the extreme values of 3.6 K and 0.10 K are taken as the temperature difference in the cavity, this results in a variability in the thermal resistance value of approximately +/-12% for emissivity factors (E) of 0.85, 0.90 and 0.95 respectively.

However, if the mean temperature of 2 K, which is more likely to be encountered in practice, is taken as the temperature difference in the cavity, this model indicates that the thermal resistance value in an airspace cavity shows considerably less variation. The uncertainty in cavity resistance is 0.180 +/- 5% given the likely variations in surface emissivities and temperature differences which may be encountered in practice.

#### 4.1.2 Area weighted model

The evaluation of bridged areas is complex but where discrete bridges are concerned to a first order approximation these are taken into account by employing area weighting which is effectively a combination of 1D heat flows through the various components.

The CIBSE Guide recommends that the area weighted model can be used in the case of discrete bridges, a three dimensional analysis or the combined model should be used for the multi-webbed bridges and a three dimensional technique such as finite elements (computer program) should be used for finned element bridges (CIBSE - 1986).

#### Calculation of the area weighted value

The CIBSE Guide recommends standard procedures to deal with bridged single and twin leaf walls (inner leaf bridged or both leafs bridged). The thermal transmittance of each heat flow path can be calculated separately and then added together in direct proportion to their areas. Where the outer leaf of the wall constructions is brick, and the conductivity of the brick is nearly the same as the mortar's (0.8 W/mK), the outer leaf is considered to be homogeneous and only the case of a twin leaf wall construction with the inner leaf bridged is generally considered. For this condition the overall  $\Lambda$  value is given by:

$$\Lambda = \frac{1}{R_b + R_h} \quad (4.3)$$



where:

$R_h$  = thermal resistance of the homogeneous leaf ( $\text{m}^2\text{K/W}$ )

$R_b$  = thermal resistance of the bridged leaf ( $\text{m}^2\text{K/W}$ )

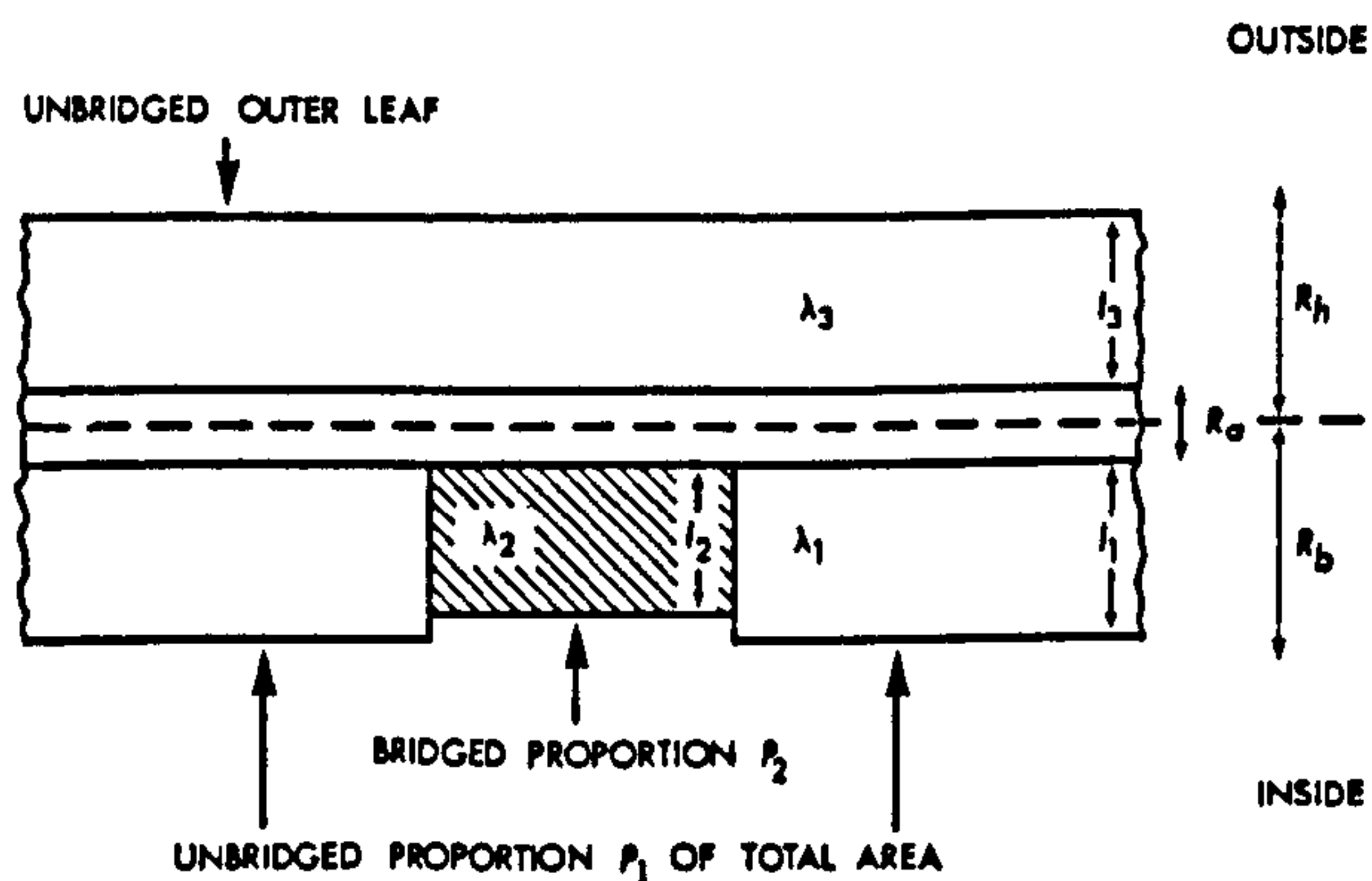


Fig. 4.2:

*Twin leaf wall - inner leaf bridged*

*(After CIBSE Guide - Section A3 - 1986)*

The boundary between the two leaves is taken as mid-way across the air gap so that half the air gap resistance is added to each leaf. Thus the resistances are:

$$R_h = \frac{1}{2} R_a + \frac{l_3}{\lambda_3} \quad (4.3a)$$

$$R_b = \frac{1}{\frac{P_1}{R_1} + \frac{P_2}{R_2} + \frac{1}{2} R_a} \quad (4.3b)$$

and in this case:

$$R_1 = \frac{l_1}{\lambda_1} + \frac{1}{2} R_a$$

$$R_2 = \frac{l_2}{\lambda_2} + \frac{1}{2} R_a$$

There is an analogous treatment for the other conditions of bridged single leaf walls and twin leaf walls (both leaves of the wall bridged).

### **Applicability of the model**

The model can be applied in the case of discrete bridges and it is recommended especially in the case where a mortar joint of a conductivity greater than the adjoining block work is present (CIBSE - 1986).

The CIBSE Guide states:

"The effect of mortar joints, can account for 5 to 20% of the area. Where the solid building material has similar thermal properties to the mortar, the effect of bridging is negligible. However, where the mortar is used with materials of substantially different thermal properties, the effect of heat bridging should be taken into account. Typically, mortar has a density of  $1750 \text{ Kg/m}^3$ , thermal conductivity of  $0.8 \text{ W/mK}$  for the inner leaf and  $0.9 \text{ W/mK}$  for the outer leaf and a thickness of 10mm" (CIBSE Guide, Section A3 - 1986).

Along with the CIBSE Guide, several workers have also emphasised the applicability of this model [(Matthews (1982), Rose (1983), Fulmer-Yarsley (1989))].

#### **4.1.3 Slotted block model**

There are two main variations used to deal with slotted blocks, the combined model recommended by the CIBSE Guide (CIBSE - 1986) and the Anderson model (Anderson - 1981-II). Both models are examined in turn.

##### **The combined model**

The thermal resistance of slotted blocks may be calculated by the combined model which is applicable to masonry or concrete blocks with a pattern of filled or unfilled rectangular voids (CIBSE - 1986).

The pattern of heat flow in a block with voids is complicated mainly due to the effects of lateral heat flow around the voids and the effects of adjacent materials. Commenting on this particular method, Anderson (1981-II) states that "this method can give a reasonable result when the slots are very large relative to their separation, but it will always overestimate the thermal resistance, and hence underestimate the U value".



The method involves, dividing the block into slices of similar construction, and setting of upper (based on 1D heat flow) and lower (based on parallel isotherms) limits to the degree of lateral heat flow and calculating a mean equivalent thermal resistance of the block. The model gives a unique value for a particular block. The combined model gives an equivalent resistance which is then used in the normal manner to obtain the overall  $\Lambda$  value for the composite construction that contains the block (CIBSE - 1986).

### **The Anderson model**

Anderson (1981-II) proposed a model to calculate the thermal transmittance value for a wall construction which contains slotted blocks. It is a more sophisticated version of the combined model. The model was tested against BRE's 2D finite element computer program, by examining the effect resulting from changing slot size for a range of slot configurations.

### **Applicability of the model**

The combined model is a simpler calculation procedure to apply than the Anderson model and results in an equivalent mean thermal resistance value of the slotted block. On the other hand the Anderson model is a more sophisticated version than the combined model and results in the final  $\Lambda$  value of the wall construction.

In practice the manufacturers trade literature nearly always provides the designer with resistance values for slotted blocks or perforated bricks. However, the method used to determine these values is not given.

A limitation of the two variations is that no standard procedure is recommended to take into account the mortar joints which as Anderson (1981-II) states "can have an appreciable effect on the total heat transfer, particularly when the mortar is of higher density than the block material".

As far as the present study results are concerned, taking into account the cold bridging by the mortar joints in the case of a wall construction containing slotted blocks, the area weighted model is applied again with the resistance of the slotted block in place of the resistance of a solid block.

## **4.2 The Two - Dimensional (2D) model**

The 2D models are mainly computer based models, and have been used extensively by a number of workers. For example, the work done on mortar joints and their effect on the average performance of the wall by McIntyre (1984) and Siviour and Mould (1988).

McIntyre (1984) examined heat loss through mortar joints in some detail. He suggested that the heat flow round a mortar joint is severely distorted. He compared several variations of dimensions and thermal constants of a plastered inner leaf calculated using the CIBSE area weighted value with the value resulting from a detailed 2D computer program using finite element analysis. It was shown that the effect of thermal bridging by the mortar was rather worse than that suggested in the Guide.

Siviour and Mould (1988) assessed the thermal bridging effect of the mortar joints between the insulating blocks of an inner leaf, concluding that the effects of thermal bridging should be incorporated in the calculations for U values. They also used a 2D finite element program with the same results. They mention that improving levels of thermal insulation can result in greater discrepancies between calculation and practice if this is not done.

### **Applicability of the model**

The model is applicable in situations where it is considered that the heat flow through the wall is adequately represented in two dimensions, such as the heat flow through a lintel within a wall (some distance from the edges). However, there are situations where 2D representation is not adequate such as finned element bridges and mortar joints. These can only be assessed satisfactorily by 3D models (CIBSE - 1986). Finally, it must be mentioned that the 2D models are now being gradually superceded by more powerful 3D computer packages.

## **4.3 The Three - Dimensional (3D) model**

Where a more detailed representation of the average performance of the wall is required, a 3D model must be used. Following the rapid advancement of computers there are now a number of packages available.

In the present study a steady state three dimensional finite element package (a brief review of the finite element technique is given in Appendix A) was used to characterise the wall heat flux and temperature profile for representative sections of the construction types investigated.



The thermal analysis package, termed the Analyzr, is produced by Sampson Technical Consultants of the USA (1986) and is a system of Fortran routines designed to efficiently handle all phases of thermal network analysis for temperatures and heat flows in a physical system.

The technique subdivides the region into elements with the nodes located at the element boundaries. A function often termed the "basis function" is developed for each element. The basis function is usually a linear function of space and, in a transient solution, time, i.e.  $T(x,y,z,t)$ . The next step is to minimise this function by integration over the region. The net product is a set of linear equations for the node temperatures. These are then solved by matrix inversion techniques which yields the nodal temperatures and subsequently heat flows.

### **Geometrical Modelling**

It is desirable in thermal analysis to have the conductors which form the thermal model at approximately the same conductance value or at least have adjacent conductors that are of the same order. This prevents the solution being unstable and reduces computational time.

The size of conductors is governed by the element definition and the material property. The penalty for having too fine an element mesh is that the size of the model soon exceeds the capacity of the programme or the computer. Therefore a balance has to be struck between element size and model size.

### **Modelling Conditions**

The modelled section was divided into a series of elements and associated corner nodes. The resultant mesh was designed to accommodate the mortar joint dividing the inner blockwork in the horizontal and vertical planes. Each element had its material properties individually specified and corresponded to those supplied by the manufacturers.

The boundary conditions and specific modelling conditions applied for each individual model of the walls investigated are detailed in chapter 6.

### **Uncertainties**

The accuracy of the finite element technique is limited by the underlying assumptions that an infinite number of discretized elements tend to a continuous media and thus describe totally the field variable (temperature) at all locations. In this hypothetical case the

approximation functions have no influence on the solution. However, the thermal modeller does not have the luxury of infinite computer capacity and therefore the accuracy of a solution depends on the degree to which the approximation functions and the discrete elements describe the solution domain. It is not therefore possible to provide a definitive estimate of the accuracy of a model without either knowing the solution, (in which case why use a finite element model), or having access to infinite computer capacity. In a 1D steady state case the accuracy is no less than the result given by the application of Fourier's Law of conduction, provided the elements are homogeneous. In this case the elements size is immaterial to the solution as the approximation function describes accurately the field variable throughout the elements (Armstrong - 1990).

### **Applicability of the model**

The model can be applied where a more detailed representation of the heat flow is required, such as at the edges of a lintel within a wall, finned element bridges, window corners, etc.

The wall cavity is treated as having a thermal resistance value of  $0.180 \text{ m}^2\text{K/W}$ , the value recommended by the CIBSE Guide - Section A3, consequently the uncertainty involved in the determination of this value is present in the 3D model as well.

When the problem becomes multi-dimensional with the field variable value changing rapidly in the solution domain, the underlying accuracy of the solution will be based on a realistic judgement of how best the limited number of elements available, dictated by computer capacity, can be applied to achieve the best approximation to a continuous solution domain. Finally, the finite element model, like any model, relies on the accuracy of the specified boundary conditions and their appropriate use. In this regard it should be noted that in the work undertaken, although three dimensional in nature, isotropic material properties were assumed (Armstrong - 1990).

## **4.4 Tolerance in building components**

Any application of a model to real problems related to heat transfer will require that numerical values are available for the necessary physical dimensions and physical properties of the material under consideration.



#### **4.4.1 Physical dimensions**

The dimensions of height, length and thickness are all relevant with respect to the 1D, 2D and 3D models. The only exception to this, is in the case of the basic 1D model where only material thickness is considered. The major factor which determines the element's thermal performance in the calculation procedure is the thickness of the component layers. Table 4.2 is only concerned with the maximum allowable deviations in the thickness of the building components according to the appropriate British Standards. Since the values for the dimensional tolerances are given in units, the Standards have been interpreted to give a percentage variation and this is presented in column 4 of Table 4.2 for particular component thicknesses.

#### **4.4.2 Thermal conductivity of building materials**

Heat conduction is, basically, the transmission of energy by molecular motion and thermal conductivity is then, the physical property denoting the ease with which a particular substance can accomplish this transmission. The thermal conductivity of a material is found to depend on the chemical composition of the substance, or substances, of which it is composed, and whether or not it is homogeneous.

Many of the engineering materials encountered in practice are not of a homogeneous nature. This is particularly true of building materials and insulating materials. Some materials may exhibit non-isotropic conductivities that result from a directional preference caused by a fibrous structure as in the case of wood, asbestos, etc.

There exist non-porous and porous materials. Non-porous materials include glass and metals where the mechanism of heat transfer is mainly by conduction.

Heat can be transferred through porous materials such as aerated concrete blocks, by four processes: conduction through the solid phase, conduction and convection through the gas phase, and radiation between solid surfaces, the relative importance of each process depending on the internal structure of the respective body as well as on the moisture and temperature.

Inhomogeneities may be present in the material because of its porous nature (glass wool, cork, etc.) or because it is composed of different substances (concrete, brick, etc.). In any of these instances the thermal conductivity may vary from sample to sample due to variations in structure, composition, density or porosity.

COMPONENT	PERMISSIBLE MAXIMUM DEVIATION IN THICKNESS OF COMPONENT	SOURCE	% CONVERSION FOR DEVIATION IN THICKNESS OF COMPONENT
Brick	+2 mm      -2 mm	BS 6073: Part 1: 1981	±2% for a brick of 100 mm thickness
Cavity *  (overall thickness of walls)	±15 mm	Based on BS 8000: Part 3: 1989	±10% or ±20% of cavity width
Extruded Board Insulation	10 to < 20 mm = ±1 mm 20 to < 50 mm = ±2 mm > 50 mm = ±3 mm	BS 3837: Part 2: 1990	±5% ±6%
Block	+2 mm      -2mm average +4 mm      -4 mm at any individual point	BS 6073: Part 1: 1981	±2% for a block of 100 mm thickness ±4% for a block of 100 mm thickness
Plaster  (for 13 mm thickness)	within 3 mm	BS 8000: Part 10: 1989	±23%
<p>* Tolerance limits for an airspace cavity thickness are not available. Best estimate is derived from the tolerance in the overall thickness of the wall.</p> <p>Therefore two estimates are considered:</p> <p>tolerance limits of ±5mm and ±10mm for a cavity thickness</p>			
<p><b>Table 4.2:</b></p> <p><i>Permissible deviation in the thickness of a building component</i></p> <p><i>(After British Standards)</i></p>			



The presence of pores or air-entraining inclusions within a solid lowers its thermal conductivity (Simpson and Stuckes - 1986). Insulation is used as building material to minimise radiative, convective, and gas-conductive heat transfer, while contributing only minimally to solid-conductive heat transfer. The majority of present building insulation materials are of low density and consist of many small voids containing air, separated by a large number of particles but only a small fraction of solid material.

The majority of fibrous insulations, both blanket and board product, are manufactured by processes that cause the fibres to be in a layered direction, rather than in a random orientation. When such an insulation product is applied to an insulation surface, the preferred direction is such that the heat flow is perpendicular to the fibre orientation, that is, where there are a large number of resistive barriers to the heat flow. If the heat flow is parallel to the fibre orientation the heat transmission is enhanced due to the direct contribution along the fibres.

Insulation in general, may be considered to be loose fill, flexible or rigid, which under permissible conditions can be used either in new construction or in existing buildings.

- (1) Loose fill includes mineral fibre (such as rockwool and glass fibre), cellulose, and expanded mineral aggregates (such as vermiculite and perlite).
- (2) Flexible insulation includes glass fibre or rockwool batts and blankets.
- (3) Rigid insulation includes precured foams applied in rigid form (polyurethane and polystyrene), and foams which are applied in fluid form and subsequently dry or cure in place to a rigid form (such as polyurethane and urea formaldehyde foam).

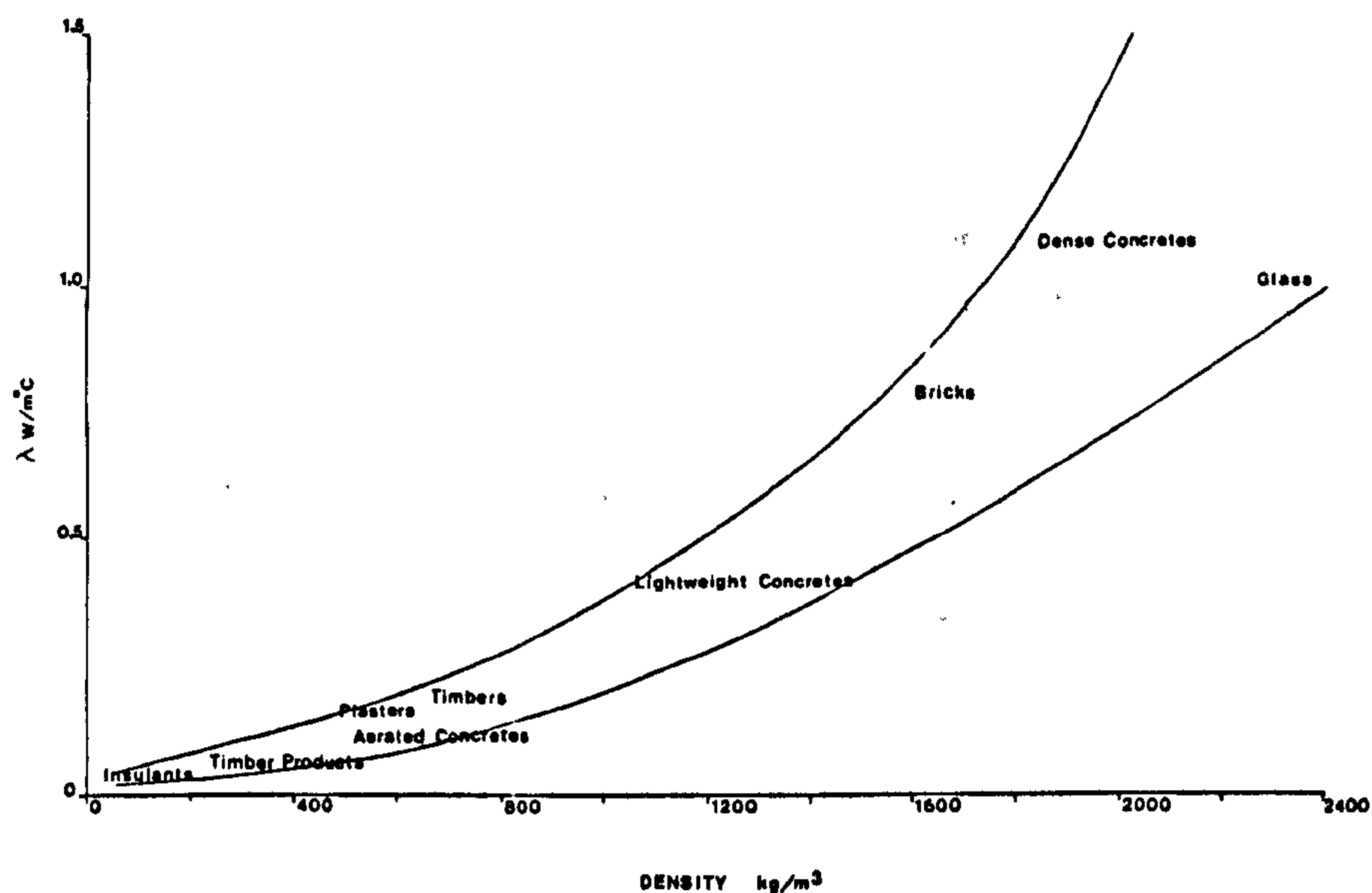
#### **Factors affecting the conductivity value**

According to Simpson and Stuckes (1986), in the built environment the conductivity of porous materials varies with density, porosity, moisture content and temperature.

##### **(1) Density:**

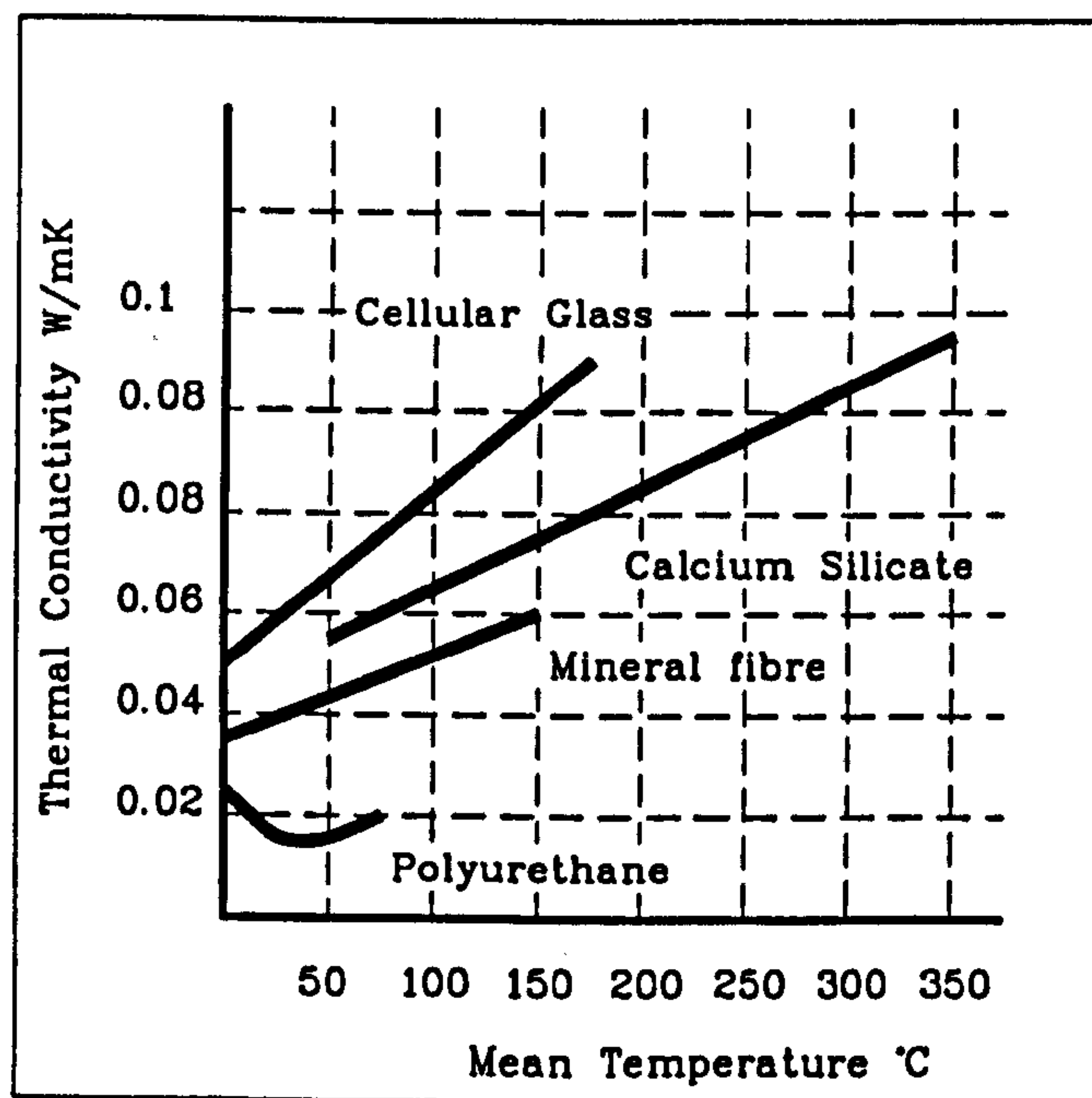
The density of the material depends strongly on the manner in which the solid material is interconnected. Fig. 4.3 illustrates the region within which most building materials lie.

The conductivity is not solely a function of the density, for example, concretes of the same weight but prepared with different aggregates may have different thermal properties. Mixes with quartzitic or siliceous aggregates tend to have a high conductivity and the use of sand as a fine aggregate also tends to increase the thermal conductivity.



**Fig. 4.3:**

*General relationship between thermal conductivity and density of building materials (After Simpson and Stuckes - 1986)*



**Fig. 4.4:**

*Typical variation of thermal conductivity with mean temperature (Adapted from ASHRAE - 1977)*



No fines-mixes, particularly when weak in cement, have a lower conductivity than mixes which include fine aggregate. The conductivity of a material appears to be determined by whether it is predominantly cellular or granular in structure, rather than whether it is crystalline (well-ordered lattice arrangement like quartz) or amorphous like glass. Studies by Tye and Desjarlais (1978) and Tye et al (1980) on low density fibrous and cellular insulations ( $<32\text{Kg/m}^3$ ) used for the building envelope have indicated that relatively small changes in density ( $<10\%$ ) can give rise to significantly large changes in the thermal performance due to the effect of radiative heat transport. When this factor is combined with changes in thickness caused by poor recovery or by compression, the total changes in thermal resistance of a product can vary by more than  $\pm 20\%$  (Tye and Desjarlais - 1983).

## **(2) Porosity:**

Density and porosity are closely related. The low density materials usually include a high proportion of enclosed air spaces within their structure. As air is a very poor conductor of heat, increased porosity results in lower  $\lambda$  values, the lower limit of conductivity in porous or fibrous materials approaches that of completely still dry air. In general, the higher the porosity, the lower the conductivity of the material.

From the conduction point of view, materials in which the air is contained in enclosed cells (cellular) conduct heat more rapidly than those in which the air space is more or less continuous (granular). The reason for this is that in cellular materials the cell walls form continuous solid paths, whereas in granular materials the path is broken at the surface of each granule.

Although porous materials are solid in one sense, they are, because of the air content, better considered from a thermal point of view as composite materials. Consequently, convection within the air spaces and radiation across the air spaces may also take place. The sizes of both the particles and the air spaces are therefore important.

## **(3) Moisture content:**

As water is a relatively good conductor of heat, when compared to air, it increases the conductivity of porous materials when it increases the moisture content of the air within the voids or, more significantly, when it replaces the air in the voids. A number of different factors affect the moisture content of materials, such as capillarity, absorption, permeability and the saturation coefficient.

The effect of moisture content on the thermal conductivity of some masonry materials is that the presence of water may double the thermal conductivity, which may result in increased heat transfer and energy requirements. If precautions are not taken, a build up of moisture may contribute to the deterioration of building materials. The effect is equally applicable to many other porous materials and emphasises the importance of ensuring that materials are

kept dry, particularly those with low conductivities.

The presence of moisture in insulation products contributes to reduction in thermal performance. Proper design, careful installation, and the use of adequate moisture retarders will ensure that the effects of the water vapour and moisture are minimised.

#### **(4) Temperature:**

In general, the conductivity of insulating materials tends to increase as the temperature range over which it is measured increases. The transparency of a thermal insulation to thermal radiation becomes important as the temperature increases, and as temperature differences across the materials increase. For homogeneous materials, the primary mode of heat transfer is conduction; but, as temperatures and the transparency of materials increase, the heat transfer by thermal radiation and convection becomes a greater part of the total heat transferred. The magnitude of radiation and convection transfer depends largely on temperature, the nature of materials involved, and geometric considerations. While conductivity is not constant with temperature, it is sensibly constant for the relatively narrow temperature band to which building materials are subjected. Typical variations of conductivity with mean temperature are shown in Fig. 4.4.

#### **Thermal conductivity values**

It has been common practice for many years to adopt thermal conductivity values based on historical (generic) data for broad classifications of materials. For the majority of masonry materials an empirical relationship between density and thermal conductivity has been used.

Appropriate values of thermal conductivities and other properties of construction materials, drawn mainly from historical data are included in the CIBSE Guide - Section A3. There is a wide range of values that are not product specific. The values reported from these different sources, are typical values and a considerable deviation from these values may be expected depending upon the manufacturers building products used in the construction. When comparing the expected with the actual performance of a construction it is not the generic data that is of interest but the manufacturers product data.

There is great difficulty in establishing the variability limits in the thermal conductivity of a building component, because appropriate data would not appear to be available. The expectation is that manufactured products such as rigid board insulation will have a much smaller variability than bricks and blocks. Trying to quantify the variability for different building materials was proven to be extremely difficult. The best evidence available is Table 4.3 supplied by the National Physical Laboratory (NPL) [incorporating the British



Calibration Service (BCS) and the National Measurement Accreditation Service (NAMAS)].

MATERIALS	RANGE OF THE THERMAL CONDUCTIVITY VALUE	BEST MEASUREMENT CAPABILITY EXPRESSED AS AN UNCERTAINTY	TEMPERATURE RANGE	SOURCE
Homogeneous	from 0.01 to 0.15 (W/mK) from 0.15 to 1 (W/mK) from 1 to 2 (W/mK)	$\pm 3\%$ $\pm 5\%$ $\pm 7\%$	-10 °C to 80 °C	I Goodier of NPL
Masonry	Density up to 900 Kg/m <sup>3</sup> and thermal conductivity up to 0.25 W/mK  Density 900 to 1500 Kg/m <sup>3</sup> and thermal conductivity 0.2 to 0.6 W/mK  Density 1500 to 1850 Kg/m <sup>3</sup>  Density above 1850 Kg/m <sup>3</sup>	$\pm 5\%$  $\pm 5\%$ to 7.5%  $\pm 7.5\%$ to 15%  $\pm 10\%$ to 20%	-10 °C to 80 °C	I Goodier of NPL

**Table 4.3:**

*Uncertainty limits in the thermal conductivity value of homogeneous  
and masonry materials*  
*(Based on Goodier - 1990)*

The values in Table 4.3 are recommended and used by different testing houses in Britain such as Harry Stanger Consultants and they represent the best measurement capability expressed as an uncertainty. Following correspondence with a number of specialised laboratories and in the absence of more precise information it was found appropriate to interpret these values as the variability in the conductivity value for the building materials used in the construction.

#### **4.4.3 The effect of the uncertainty in the dimensions and material properties in the thermal conductance value ( $\Lambda$ value) calculation**

Assuming the perfect model, uncertainties in the knowledge of the physical dimensions and thermal properties of the materials used in the model will introduce an uncertainty in the final value. Consequently, all models whether they are 1D, 2D or 3D embody the fundamental problems of:

- (1) dimensional tolerances
- (2) thermophysical properties of the materials
- (2) uncertainty in the behaviour of the wall cavity

The combined uncertainty due to these sources can only be evaluated in relationship to a specific form of construction and can only be tested empirically.

An attempt was made to quantify the uncertainty limits of the  $\Lambda$  value of a wall, due to the uncertainties in physical dimensions and the thermal properties of its components. This was carried out by applying both the "Monte-Carlo" statistical method and statistical treatment of errors according to Pentz and Shott (1988) to the 1D steady state basic CIBSE model to three different types of wall construction. The constructions were: brick/clear cavity/lightweight block, brick/partially filled cavity/block and brick/fully filled cavity/lightweight block. These types were chosen because they are representative of current construction practice, their performance had been measured as part of the present study and finally because in each type there is one different component which is dominant in the overall performance of the wall. In the first type it is the lightweight block, in the second the insulation layer (rigid board) and in the third the fully filled cavity.

The statistical treatment of errors is based on the model provided by Pentz and Shott (1988) which is as follows: "assuming that independent measurements  $\lambda$  (conductivity) and  $L$  (thickness), which have total errors  $\Delta\lambda$  and  $\Delta L$  associated with them, are combined to give the result  $X$ , which has error  $\Delta X$ " then:

$$\text{if } X = \lambda + L$$

$$\Delta X = \sqrt{(\Delta\lambda)^2 + (\Delta L)^2}$$

$$\text{or } X = \lambda - L$$

and

$$\text{if } X = \lambda * L$$

$$\Delta X/X = \sqrt{(\Delta\lambda/\lambda)^2 + (\Delta L/L)^2}$$

$$\text{or } X = \lambda/L$$



The "Monte-Carlo" method is used to solve problems by constructing for each problem a random process whose parameters are equal to the required quantities, making observations on the random process, and estimating from these observations the values of the parameters of the process. The required quantities in this case are the thermal conductivity and thickness of the layers comprising the wall construction (for a more detailed explanation on "Monte Carlo" methods see Hammersley and Handscomb - 1964).

Therefore for each layer of the wall the thickness and the conductivity were generated using a Monte-Carlo technique. The thicknesses and conductivities were assumed to be normally distributed about their mean values. These normal distributions were used as the basis for predicting the physical quantities for each layer. This enabled a resistance for each individual layer to be computed and by taking sufficient estimates, the normal distributions of the wall constructions could be obtained along with its standard deviation. The input distributions were plus or minus 3 standard deviations (99% confidence limits) for all materials, consequently the output values are plus or minus 3 standard deviations.

The resulting errors are small. The values are presented in Table 4.4 and may be applied to the CIBSE 1D basic model. It appears that the values resulting from the "Monte-Carlo" method are consistently lower than the values resulting from the Pentz and Shott method but show a similar pattern. The results from the latter method are taken as more representative, being a more pessimistic estimate. Where control of dimensions can be exercised as in the case of block, brick, insulation slab, etc., the uncertainty involved in a  $\Lambda$  value calculation is approximately  $\pm 4\%$ . However, in the case of a wall cavity there is less control of dimensions, whether the cavity airspace is fully filled or not. When the cavity is fully filled, the range of the uncertainty involved in the calculation of the  $\Lambda$  value increases considerably, depending on the variability in the thickness of the cavity (uncertainty range is  $\pm 6.70\%$  for a variability in cavity thickness of  $\pm 10\%$  and  $\pm 12.30\%$  for a variability in cavity thickness of  $\pm 20\%$ ).

Wall construction	$\Lambda$ value	Traditional Statistical Treatment of Errors	Monte - Carlo Statistical Method
Brick/ Airspace Cavity/ Aerated Block/ Plaster	0.76	+/-4.20%	+/-3.10%
Brick/ Partially Filled Cavity with Rigid Insulation Board/ Block/ Plaster	0.60	+/-4.30%	+/-3.20%
Brick/ Fully Filled Cavity with injected mineral fibre insulation/ Aerated Block/ Plaster	0.35	+/-6.70% for a variability in cavity thickness of +/-10%  +/-12.30% for a variability in cavity thickness of +/-20%	+/-5.00% for a variability in cavity thickness of +/-10%  +/-11.30% for a variability in cavity thickness of +/-20%
<b>Table 4.4:</b> <i>Maximum uncertainty limits in thermal conductance value (<math>\Lambda</math> value) calculation</i>			



**MEASURED  
INSITU PERFORMANCE  
OF  
THE WALL**

**CHAPTER 5**

## **5.0 Introduction**

The process of thermal transmittance measurement will always have uncertainties attached to it. It is important to set these uncertainties into context and discuss them before providing the results of the insitu measurements.

The uncertainties involved in a thermal transmittance measurement system are outlined in Fig. 5.1 and they can be divided into three distinct types:

- (1) physical measurement errors resulting from the calibration of the sensors, the way the sensors are attached to the wall surface and the boundary conditions to which they are subjected
- (2) data processing errors resulting from the way the data are encoded and processed
- (3) data analysis errors resulting from the analysis technique used to recover the steady state thermal transmittance value from the processed data.

These topics are examined in detail in the present chapter, firstly on an individual basis and secondly, on a combined basis to give an overall assesment.

In previous chapters it was emphasized that the uncertainties involved are a function of the actual system used. Consequently, the error analysis in this chapter is in terms of the particular system/equipment used and the particular types of wall construction which are involved, since these present the physical context in which measurements are taking place. It is only in this physical context, that a realistic assesment of the errors involved in the process can be made.

### **5.1 Uncertainties/errors of the physical measurement**

Although the insitu measurement of thermal transmittance may appear to be simple, this is not the case, since a number of systematic and random errors have to be considered. The experimental value is a function of the characteristics of the HFSs and temperature sensors, the context in which they are used and the surroundings, namely:

- (1) sensor calibration
- (2) the attachment of the sensors to the wall surface
- (3) the boundary conditions at the surface.



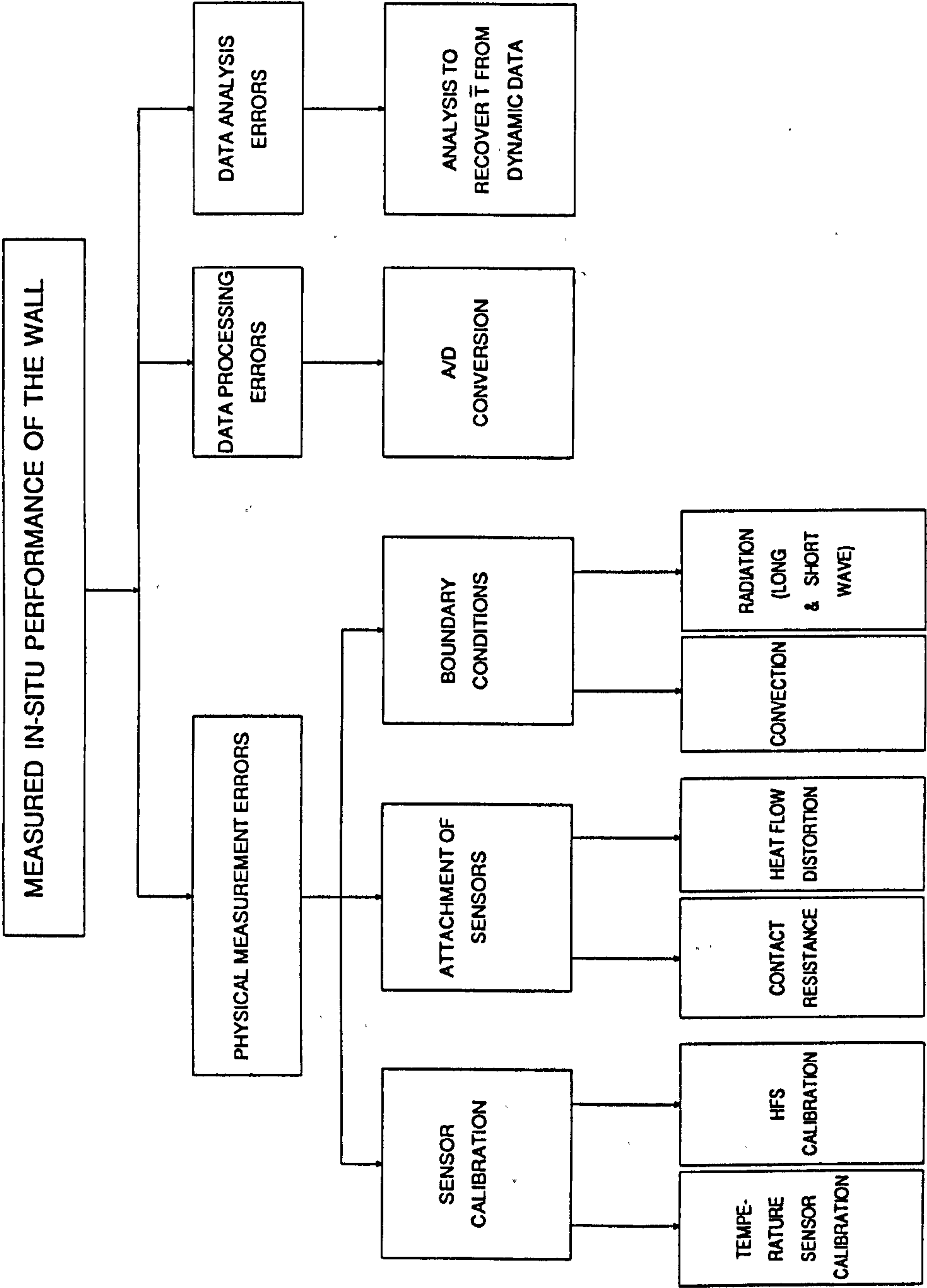


Fig. 5.1:

*Errors involved in an insitu thermal transmittance measurement*

### 5.1.1 Sensor calibration

Sensor calibration is concerned with the error introduced by both the HFSs and the thermistors, since the estimate of thermal transmittance is obtained by dividing the heat flux value by the temperature difference across the construction. The following analysis is based on steady state conditions. Details about the sensors are given in chapter 3.

#### Temperature Sensors - (Mini-Thermistors)

The sensors are highly stable with a drift of less than 0.002 °C in eight years at 25 °C. The maximum uncertainty in the calibration of an individual sensor is +/-0.1 °C in the range 0 to 70 °C.

In addition, there is a correction factor to be added to each temperature sensor which is dependent upon the length and temperature of the cables attached to the sensor. The correction factor is small being 0.0004 °C/m at 0 °C and 0.0011 °C/m at 20 °C. In practice, ten meters of cable are attached to the sensor to give:

at 0 °C a correction of  $10 * 0.0004 = 0.004$  °C

at 20 °C a correction of  $10 * 0.0011 = 0.011$  °C

Since the analysis uses the temperature difference across the wall, in terms of measurement error it is the difference between sensors which is important. Taking the worst possible case of 10 meters of cable at 0 °C and 20 °C respectively gives a differential correction of  $0.011 - 0.004 = 0.007$ . For a 20 °C difference the upper estimate of the percentage error is:  
 $0.007 * 100/20 = 0.035\%$ .

The maximum difference between any two temperature sensors over the expected range of operating conditions is the sum of the calibration errors and the temperature correction factors. The latter has been shown to be negligible giving a temperature difference due to calibration of +/-0.02 °C. The uncertainty involved is a function of temperature difference being 2% at 10 °C temperature differential and falling to 1% at a differential of 20 °C. For any sensor pair this introduces a systematic error with the magnitude depending upon the particular combination of temperature sensors used to carry out the measurement.



## Heat Flow Sensors (HFSs)

The calibration constant for every sensor is approximately 6 (W/m<sup>2</sup>mv) at 20 °C. There is also a temperature correction factor of +0.04 (%/K) which has to be applied at the temperatures that measurements are carried out. Consequently, for average internal ambient temperatures of 20 +/- 5 °C during the monitoring period, this introduces an extreme error of  $5 * 0.04 = 0.2\%$ .

Of major concern is the systematic error introduced by the calibration of each individual sensor of +/-5%, value which is highly stable with time, ten years plus (TNO - TH - 1987).

### HFS and temperature sensor error estimation

For any HFS and thermistor pair there are systematic errors introduced in the measurements where the heat flux (Q) is measured within a maximum error of +/-5% and the internal/external wall surface temperature difference ( $\Delta T$ ) is measured within a maximum error of +/-2%.

Consequently for the combination of heat flow and temperature difference:

$$\frac{Q \text{ +/-5\% error}}{\Delta T \text{ +/-2\% error}}$$

and defining the two extreme limits:

$$Q/\Delta T = 1.05 / 0.98 = 1.07$$

$$Q/\Delta T = 0.95 / 1.02 = 0.93$$

Consequently the maximum expected systematic error due to this combination is potentially +/-7%. If this encompasses all measurements, and if the HFS and temperature sensor sets are randomly selected, it is anticipated that the systematic error introduced, will be normally distributed with a mean of 1.0 and a range of 14% (+/-7%) which yields a standard error of  $14/6 = 2.3\%$ , where 6 is the number of standard deviations to encompass 99% of the measurement sets. In order to minimise the errors from this source two steps were taken, the heat flow and temperature sensors were grouped into sets (chapter 3) and an experimentally determined calibration value was derived for each set.

## **Experimental determination of sensor calibration errors**

In order to derive a calibration value for each individual sensor set an experiment was carried out, to determine the "relative" calibration of the measurement sets. The measuring sets were placed on a test wall of uniform construction in an environmental chamber and were rotated i.e. their positions were interchanged in order to determine the difference between the sets when measuring nominally the same wall construction (Plate 5.1 and Fig. 5.2).

### **Method**

The procedure recommended by McIntyre (1985) was followed:

The test room was heated continuously for at least three days prior to the measurement.

Thermal imaging was used for HFS placement.

The minimum recording duration was 72 hours.

An inside/outside minimum temperature difference of 15K or more was maintained.

The test chamber was left undisturbed 24 hours before the commencement of each measurement period, in order to ensure stabilised conditions.

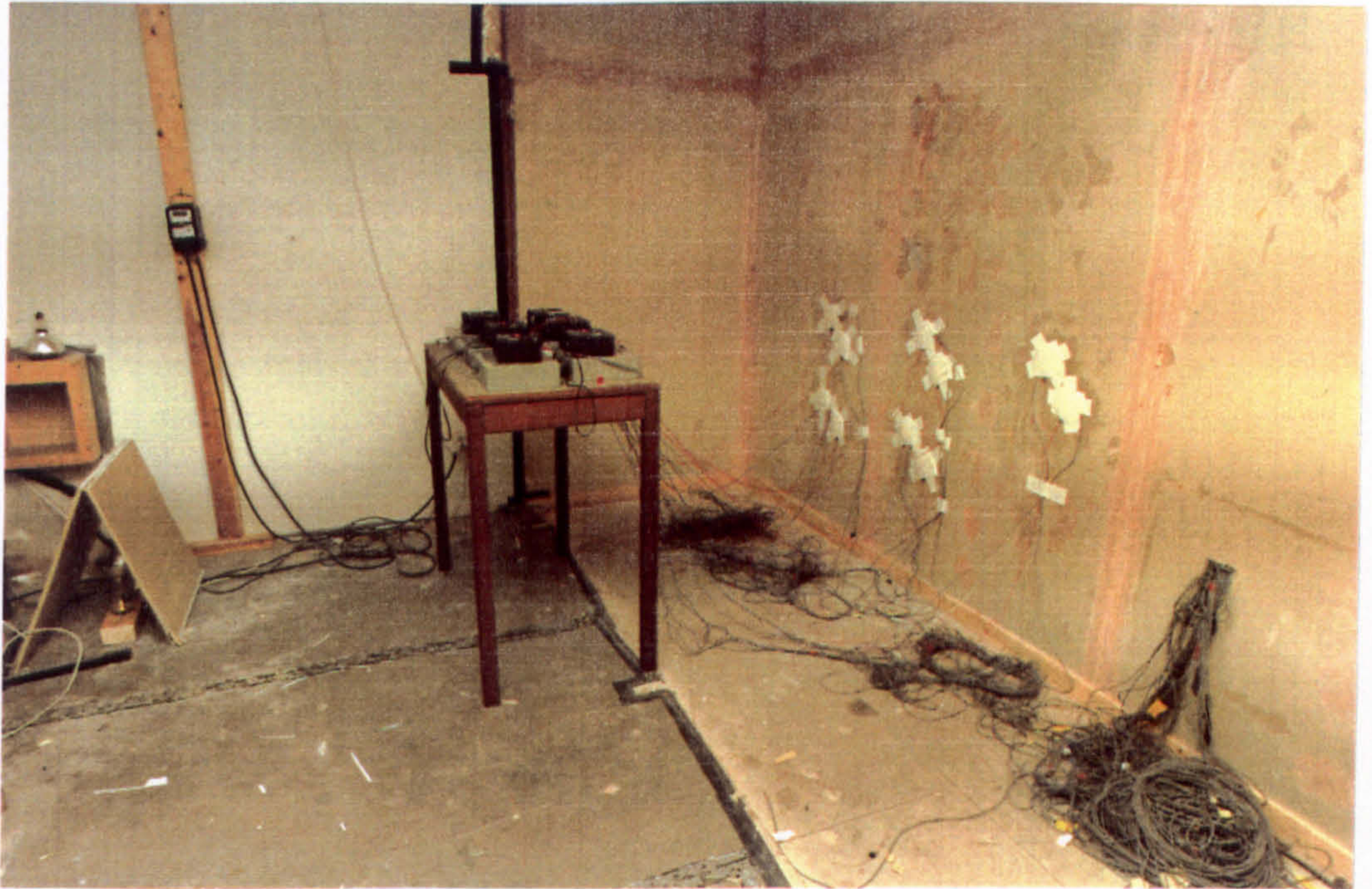
The continuous, steady internal temperature, was achieved by means of six Philips (R125) 150 W lamps, positioned at the back end of the test room and controlled by a Eurotherm Proportional Controller. Gypsum plaster screens were used to cover the six bulbs, to protect the sensors from the emitted radiation (Plate 5.1).

The recording interval was set to be 15 minutes for all parameters. Readings were obtained over a total duration of 72 hours for each set of measurements and the results were time averaged.

### **Wall construction**

The construction of the timber frame test wall which was divided into six sections/panels (only the three middle sections were used for the experiment) is shown in Fig. 5.3. Rigid Wallmate CW boards [Dow Chemical Co.] with closed cell structure were used as the insulation material (Plate 5.2), for the three panels of the test wall (Fig. 5.3).





**Plate 5.1:**

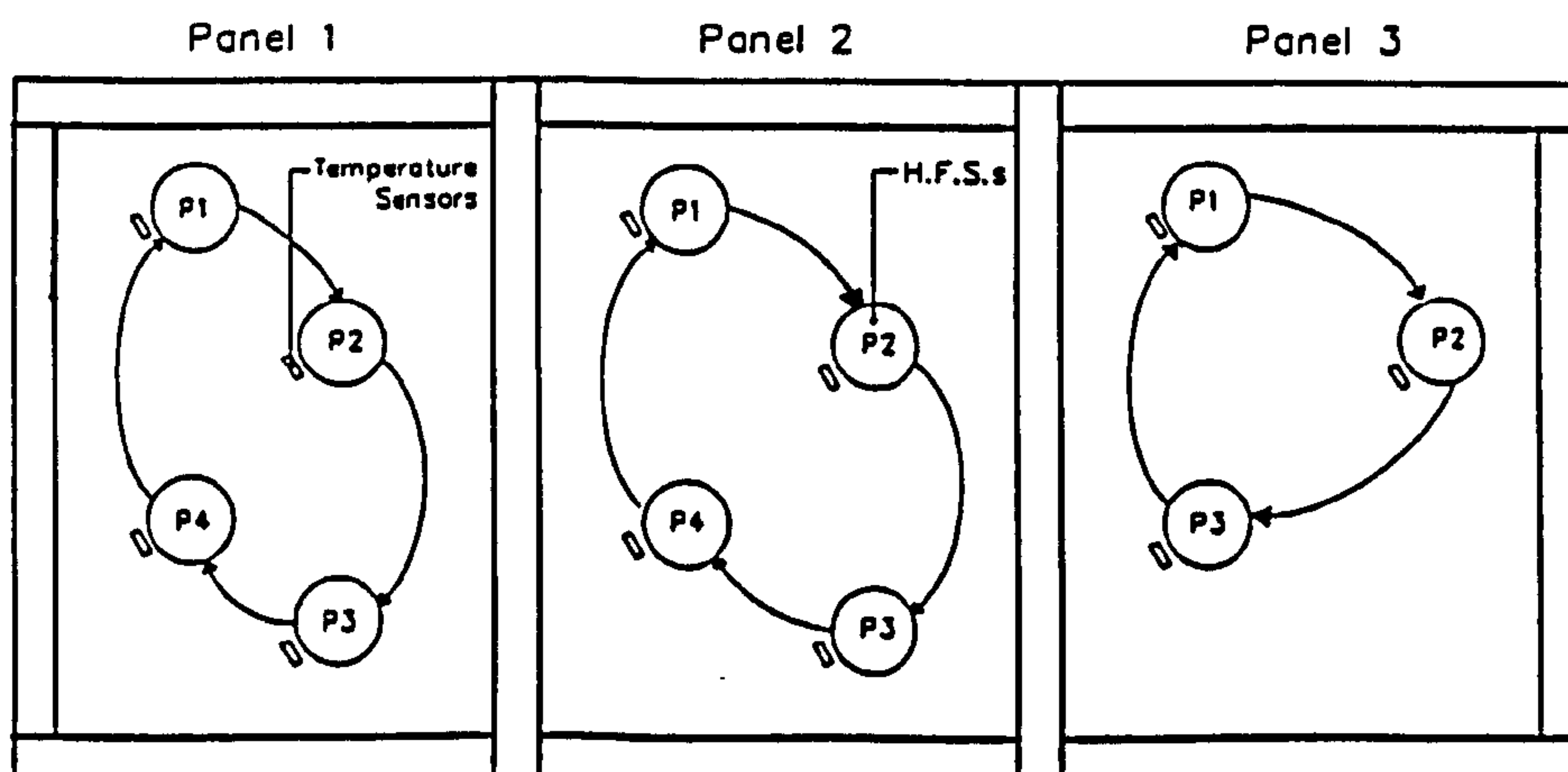
*Experimental set-up for "relative" calibration of 11 sets of sensors (internal surface of the test wall) in the environmental chamber.*



**Plate 5.2:**

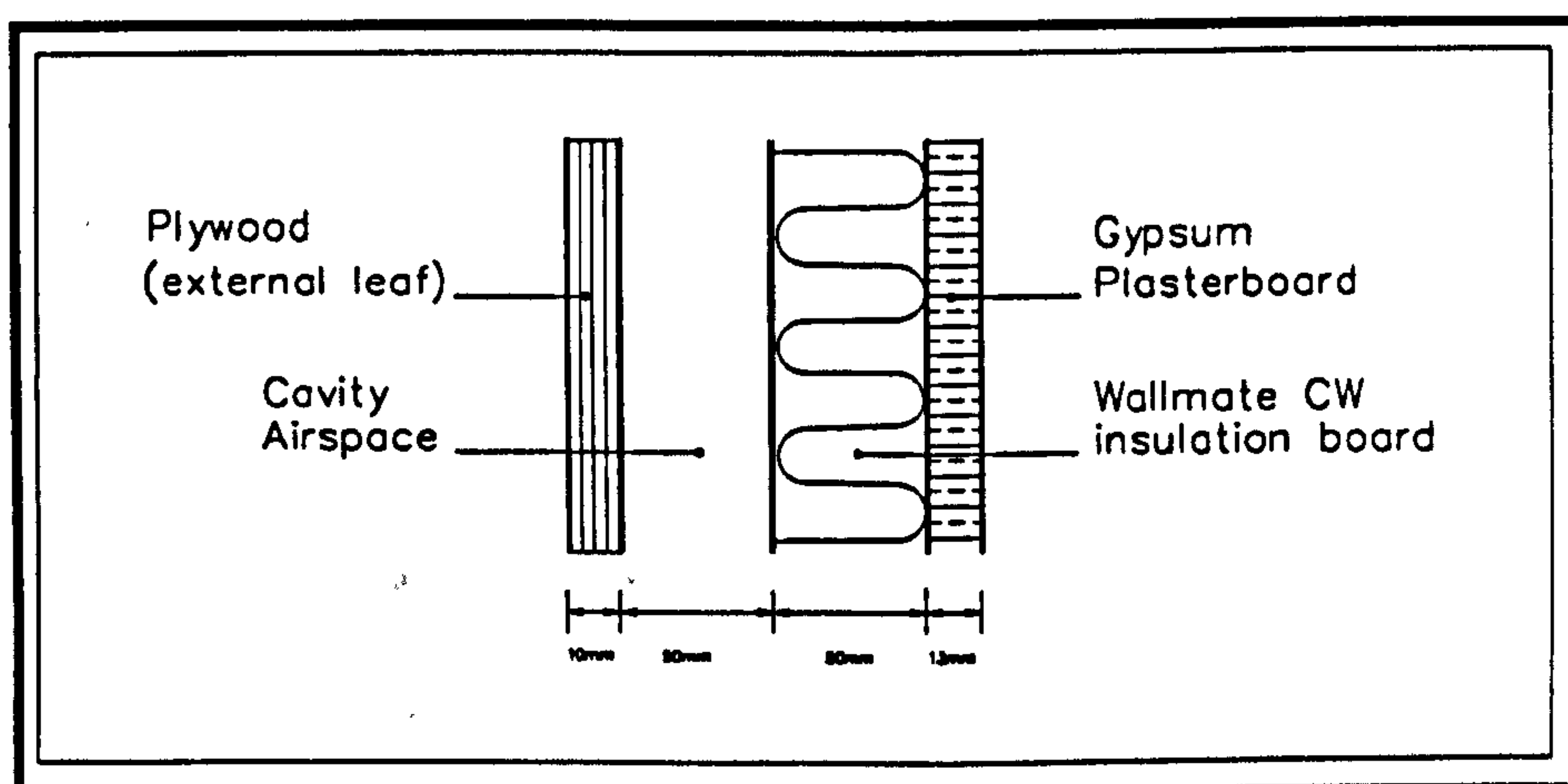
*External surface of the test wall in the environmental chamber. The rigid Wallmate CW boards (blue in colour) fitted at the three adjacent panels of the test wall can clearly be seen.*





**Fig. 5.2:**  
**Experimental set-up**

*The Fig. indicates the three adjacent panels at the internal surface of the test wall and HFS rotation pattern*



**Fig. 5.3:**  
**Section through the test wall**



Wallmate was chosen because it has a high thermal resistance and a low thermal mass, giving short settling times. Also, with it being a manufactured product, it was expected to perform within manufacturing tolerance limits and give reproducible conditions between the panels.

Eleven sets of sensors were attached to the vertical test surface using silicone grease as the bonding agent and masking tape as the fastening medium. On one test panel a typical installation would include 4 sensors placed as in Fig. 5.2, two sensors above and two sensors below the horizontal centreline of the wall.

### **Procedure**

The experimental design of Table 5.1 was adopted in order to reduce the number of measurement points. The X's correspond to the allocated positions in the panels, where the HFSs were placed. HFSs Nos: 72, 67 formed the link between panels 1 and 2 and 68, 64 formed the link between panels 2 and 3 so that the differences between the panels could be established.

Each experimental determination of the thermal transmittance took 72 hours. After each measurement the sets were rotated in a clockwise manner as in Fig. 5.2 and readings were then taken for the following 72 hours. The procedure was repeated until every unique wall position in the 3 panels had been measured by 4 different sensor sets.

At the end of the first series of measurements some HFSs were interchanged between the panels and the same procedure was repeated again for the different combination of sensors.

### **Results**

The results of the experiment are given in Table 5.2 and an Analysis of Variance was carried out to give the results shown in S/Table 5.1.

#### **Interpretation of the results**

The results give information regarding:

1. Sensor (HFS and thermistor pair) relative calibration
2. Variability of the measurements
3. The measured mean value compared to the predicted value of the test wall's thermal transmittance.

TABLE

Sensor <sup>+</sup> No.	PANEL 1				PANEL 2				PANEL 3			SENSOR AVERAGE VALUE	SENSOR AVERAGE VALUE % MEAN
	P1 <sup>*</sup>	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3		
70	X	X	X	X									
71	X	X	X	X									
69	X	X	X	X									
72	X	X	X	X	X	X	X	X					
67	X	X	X	X	X	X	X	X					
65					X	X	X	X					
66					X	X	X	X					
68					X	X	X	X	X	X	X		
64					X	X	X	X	X	X	X		
63									X	X	X		
56									X	X	X		

+

Identification number allocated for every HFS/Thermistor Pair.

\*

Position of the sensor on the panel

Table 5.1:

Experimental determination of the “relative” calibration correction factors for sensor pairs



TABLE

	Sensor <sup>+</sup> No:	PANEL 1				PANEL 2				PANEL 3			SENSOR AVERAGE VALUE	SENSOR AVERAGE VALUE ÷ MEAN
		P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3		
1	70	0.3640	0.3460	0.3620	0.3730								0.3613	0.9907
2	71	0.3775	0.3655	0.3665	0.3765								0.3715	1.0186
3	69	0.3640	0.3650	0.3720	0.3668								0.3670	1.0063
4	72	0.3420	0.3530	0.3590	0.3570	0.3710	0.3720	0.3660	0.3560				0.3595	0.9857
5	67	0.3650	0.3630	0.3730	0.3580	0.3550	0.3630	0.3500	0.3500				0.3596	0.9860
6	65					0.3665	0.3853	0.3855	0.3775				0.3787	1.0384
7	66					0.3590	0.3580	0.3468	0.3600				0.3560	0.9761
8	68					0.3690	0.3590	0.3530	0.3605	0.3690	0.3650	0.3620	0.3625	0.9940
9	64					0.3750	0.3600	0.3580	0.3690	0.3640	0.3665	0.3510	0.3634	0.9964
10	63									0.3615	0.3640	0.3565	0.3607	0.9890
11	56									0.3718	0.3735	0.3678	0.3710	1.0173
MEAN SAMPLE VALUE ➡		0.3625	0.3585	0.3665	0.3663	0.3659	0.3662	0.3599	0.3622	0.3666	0.3673	0.3593	0.3647	1.0000

<sup>+</sup> Identification number allocated for every HFS/Thermistor Pair.  
<sup>\*</sup> Position of the sensor on the panel

Table 5.2:  
Experimental determination of the "relative" calibration correction factors  
for sensor pairs - Results

1. Sensor calibration

Analysis of Variance in S/Table 5.1 (Edwards - 1968) indicated that the differences between the panel positions was not significant, while the differences between the sensors was significant at the 0.005 level.

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIGNIF. OF F
Main Effects	2449.736	20	122.487	2.072	0.029
Sensor	1889.696	10	188.970	3.196	0.005 significant
Position	561.266	10	56.127	0.949	0.502 not signif.
Residual	2069.121	35	59.118		
Total	4518.857	55	82.161		
where F = mean square value/residual value					
<i>S/Table 5.1:</i> <i>Analysis of Variance for the "relative" calibration experiment in the environmental chamber</i>					

Under these circumstances, it is permissible to average all the values across the lines in Table 5.2, subsequently obtaining the sensor average value. The HFS/thermistor pair average is then divided by the mean sample value of 0.3647 in order to obtain the relative correction factors for every measuring set (*sensor average value/mean* column in Table 5.2). In the field measurements therefore each value was multiplied with the corresponding relative correction factor.

2. Variability of the measurements

From S/Table 5.1, the mean square of the residual is due to all factors other than the sensors and positions is 59.118. This gives some indication of the random error introduced by the attachment of the sensors on the wall and to all other random sources of variation. The standard error of measurement is given by ( $\sqrt{\text{residual value/mean sample value}}$ )  $\sqrt{59.118/364.7}$  and gives a value of 2.1% for 35 degrees of freedom.



However, for measurements on a "real" wall this value is expected to be considerably higher, partly due to variations in fixing, partly due to variations in the radiation environment (longwave and shortwave). This is borne out by the analysis in chapter 6 in which the same rotation pattern was used. Results indicate that the standard error - the random effects in the measurement process vary from 2% to 4%.

### **3. Measured mean value vs predicted value**

From Table 5.2 the measured mean value is  $0.365 \text{ W/m}^2\text{K}$  compared to a value of  $0.47 \text{ W/m}^2\text{K}$  calculated according to the CIBSE Guide with a lowest mean of  $0.356$  and a highest of  $0.379$ . It is clear that there is a real difference between the measured and calculated values.

The measured value substantially underestimates the theoretical value by some 29%. This cannot be attributed to experimental error. The discrepancy may very well be due to a number of causes but in particular;

- (1) Distortion of heat flow due to the presence of the HFS on the wall surface
- (2) Contact resistance (fixing of the sensors on the wall surface)
- (3) Material properties
- (4) Cavity resistance
- (5) Presence of an air-gap between the rigid insulation board and the plasterboard.

All the above issues are dealt with in detail in later sections of this chapter, but a brief account for each one is given below:

Of these,

(1) and (2) would lead to an underestimation of the measured value. Application of Trethowen's method to correct for this effect (see section 5.1.2) gives an adjusted value of  $0.38 \text{ W/m}^2\text{K}$  for the measured value.

(3) is not likely to be a cause, since the transmittance is determined by the polystyrene properties - i.e. relatively well known. The manufacturers conductivity value of  $0.028 \text{ W/mK}$  was used to calculate the transmittance value of  $0.47 \text{ W/m}^2\text{K}$ . A value of  $0.025$  would have to be taken in order to calculate a transmittance value of  $0.43 \text{ W/m}^2\text{K}$ . This represents a 10% increase in performance, and it is thought unlikely that the manufacturer

would not claim such an enhanced performance for this product if it existed.

(4) where the standard value of  $0.180 \text{ m}^2\text{K/W}$  was used (taken from the CIBSE Guide). This would need to be  $0.700 \text{ m}^2\text{K/W}$ , in order to get a calculated transmittance value of  $0.380 \text{ W/m}^2\text{K}$ . This again is considered to be unlikely.

(5) may be a potential cause of uncertainty, since it is not taken into account in the calculation of the theoretical value, but its presence will affect the measured value by increasing the overall resistance of the test wall and therefore decreasing the transmittance. A cavity resistance of  $0.520 \text{ m}^2\text{K/W}$  must be used, which again is considered to be unlikely.

On the basis of the available evidence, every item above is, to a certain extent a potential cause and it is not possible to differentiate between them. Consequently a single reason can not be given for the difference between the measured and the calculated values. It does however serve to highlight the difficulty, in interpreting results from field measurements in the context of theoretical values.

### **5.1.2 Attachment of sensors**

The attachment of heat flow and temperature sensors on the wall surface involves two related problems. The first is the HFS and the thermistor pair contact with the surface, and the second the heat flux distortion due to the presence of the HFS on the wall surface. The local disturbance due to the sensor may cause a heat flow through the HFS that is considerably different from the surrounding regions. The heat flow through the sensor is not the same as the heat flow going through the wall, even if the boundary conditions are identical. This introduces a systematic measurement error which is dependent upon the properties of the wall being measured.

Contact resistance introduces both systematic and random errors, while heat flux distortion only introduces a systematic error (Table 5.3).

The systematic errors introduced by contact resistance and the heat flow distortion are dealt with first. This enables a fixed correction factor to be obtained which can be applied to all measurements and finally the random errors due to contact resistance are dealt with. Best current practice suggests the application of a layer of a bonding agent placed between the sensor and the wall surface in order to improve the thermal contact (sections 3.2.3 and 3.3.3 - chapter 3).



	Systematic error	Random error
Contact resistance	X	X
Distortion of heat flow	X	
<p><b>Table 5.3:</b></p> <p><i>Distribution of systematic and random errors introduced when a HFS and thermistor pair are attached to the wall surface.</i></p>		

**HFS and temperature sensors contact resistance with the surface**

On systematic errors for contact resistance, work has been done by the following:

Johannesson (1979) discusses the potential error resulting from a 1-mm gap between the sensor and the wall surface. Measured and theoretical values indicated less than 2% error up to air speeds of 1m/s.

Flanders (1985) without any experimental evidence suggests that fixing might introduce a systematic error of only 1%.

However, there are contradictory findings by Wright et al (1983) who presented an experimental evaluation of the effect of the resistance of a thermal contact, which demonstrates a possibility of substantial errors in heat flux measurement. The total thermal resistance of mounted HFSs and contact/bonding agents was determined from sensor indicated heat flows and from test-surface/sensor-face temperature differences measured with an infrared imager. Two representative makes of HFSs, one rigid and one flexible were tested, at two levels of surface roughness and with five different bonding agents under simulated field conditions. A typical 20% difference was observed between measured and calculated surface heat loss for a smooth surface (aluminium plate painted with 3M black velvet) and 30% for a rough surface (copper plate with a knurled finish). Their data are however difficult to interpret in the context of the systematic and random errors resulting from the sensor/wall surface system contact resistance.

The random errors introduced due to fixing have not been systematically investigated. However, some evidence is available partly due to the experiment in the chamber under controlled conditions and partly from the field measurements.

## **Heat flux distortion**

In a uniform material, a uniform temperature gradient produces a uniform heat flux. If, however, the thermal conductivity is changed in some part of the space, the uniform temperature gradient will not generate a uniform flux, since the flux becomes higher in the more conductive areas. This higher local flux will distort the original uniform temperature gradient to produce a complex, three-dimensionally distorted temperature field. An example, is a material containing a HFS (Figs. 5.4 & 5.5). If, the HFS has a higher thermal conductivity than its surroundings, then the heat flux through the sensor will be higher than the flux in the undisturbed material, and this high flux will distort the local temperature and heat flux fields. Conversely, if the sensor has lower conductivity than the surrounding material, the flux through the sensor will be lower than the undisturbed flux. Again, however, this low flux will distort the local temperature field (Bligh and Apthorp - 1983, Trethowen - 1985, 1986).

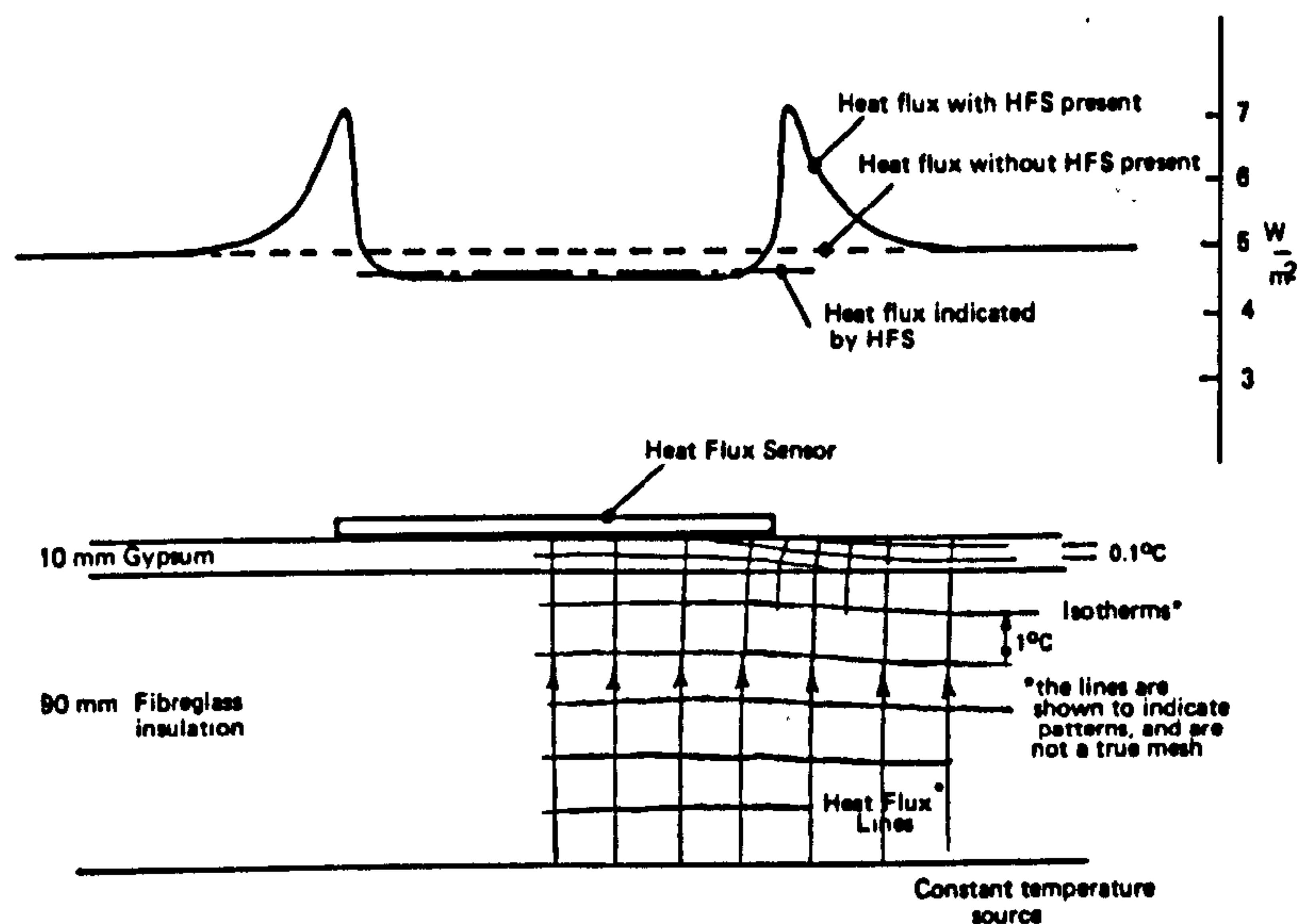
The subject of correcting the systematic error introduced by heat flow distortion has received considerable attention in both its experimental and modelling aspects.

### **Experimental**

Darnell et al. (1983) presented detailed laboratory measurements in which HFSs were placed over typical building material substrates. A guarded hot box was designed and built in accordance with ASTM Standard C236-80 to generate known heat fluxes through a variety of structural materials. These fluxes were compared with those measured by a heat flux transducer calibrated by both the manufacturer and an independent laboratory. The guarded hot plate method, ASTM C117-76, was used in the latter case. The three sets of values obtained were often in substantial disagreement, the extent of which varied with the substrate to which the transducer was attached.

The analysis of the data indicated that the cause of disagreement lay in the local distortion of the heat flux through the substrate caused by the presence of the transducer. Disturbance of the air flow over the transducer and mismatch of surface thermal emissivities of the transducer and substrate were also contributing factors. However, Darnell did not provide information to account for the observed differences.



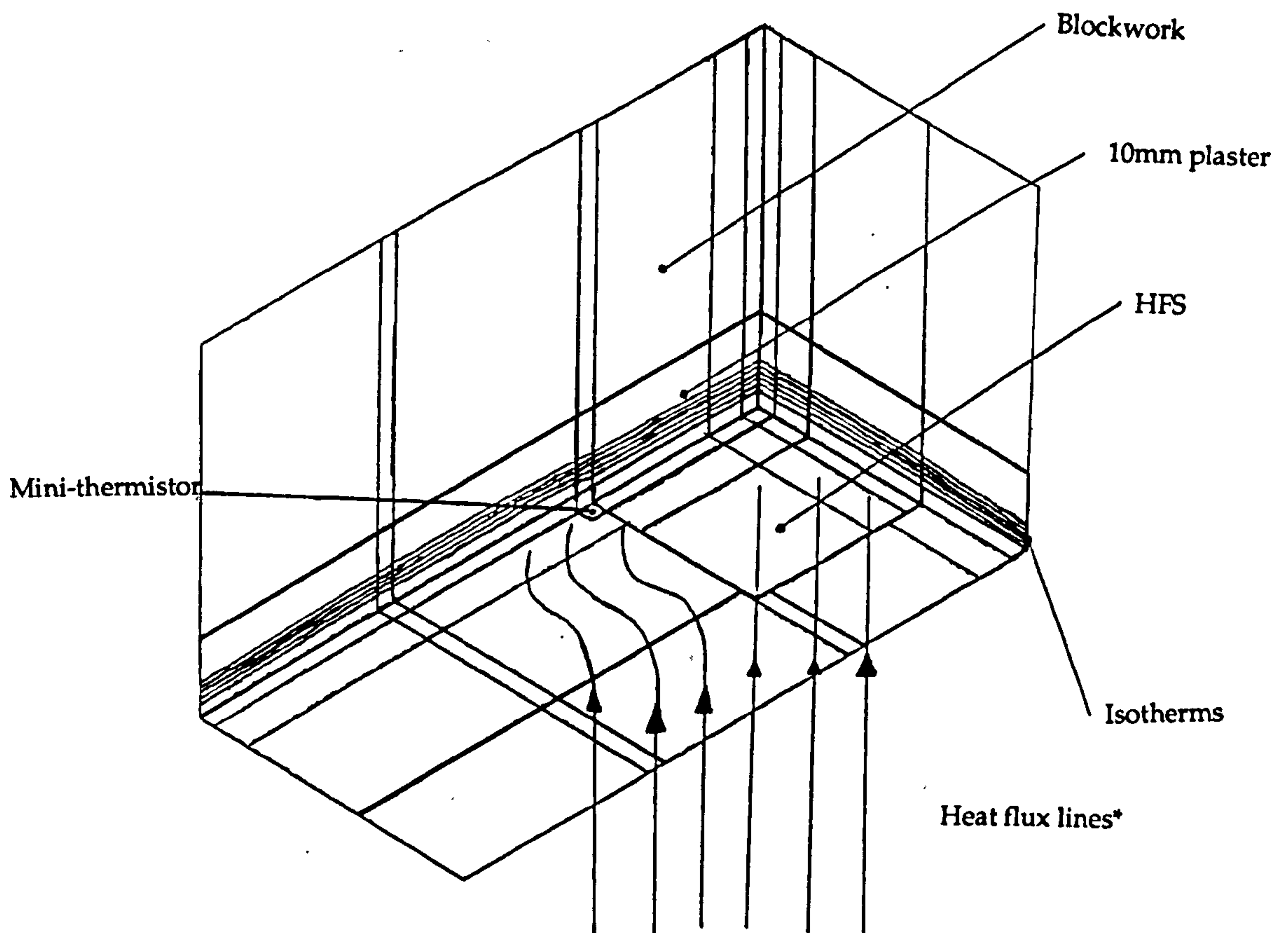


**Fig. 5.4:**

**Characteristics of heat flow around a HFS calculated using a finite difference model**

*There are two interacting systems, one system being the distribution of heat flows within the structure being measured, the other system being the surface heat transfer conditions around and over the sensor, an issue which is discussed in later sections .*

*(After Trethowen - 1985)*



\* the lines are shown to indicate patterns and are not a true mesh

**Fig. 5.5:**

**Three dimensional representation of heat flow around a HFS using a finite element model**

*The measurement error is seen as being made up of two parts, with one part attributed to the reduced heat flux where the sensor is located, the other part attributable to a portion of that reduced heat flux spilling around the edges of the sensor and thus not detected.*



## Modelling

A detailed review of previous work on analytical solutions and modelling of heat flux distortion around HFSs is given in Bligh and Apthorp (1983) and Apthorp and Bligh (1985).

Trethowen (1986) addresses the measurement error of surface-mounted HFSs for building heat flows under various physical and operating conditions. The measurement errors Trethowen seeks to explain are those attributable to the presence of a sensor, the sensor itself is assumed to be perfectly calibrated. The effects of various surface heat transfer coefficients are also allowed for. Only steady state conditions are considered. He employed a dimensionless parametric model which enables both contact resistance and heat flow distortion to be taken into account. It is valid for surface-mounted sensors, with and without edge guards. The correlation so obtained is then compared with previously reported measured errors by Darnell et al. (1983) and with an independent analytical solution presented by Weir (1986) for a limited set of conditions.

This is the most comprehensive, best validated and applicable study and provides a good basis to estimate the systematic error margin introduced in the measurements of the present study. The parametric model makes use of three dimensionless parameters,  $H$ ,  $E_{\max}$ ,  $E_{\min}$  (which they include both common and independent factors) and offers a quantitative estimate of the systematic error  $E$  (Fig. 5.6):

$$E = s c H^n$$

where

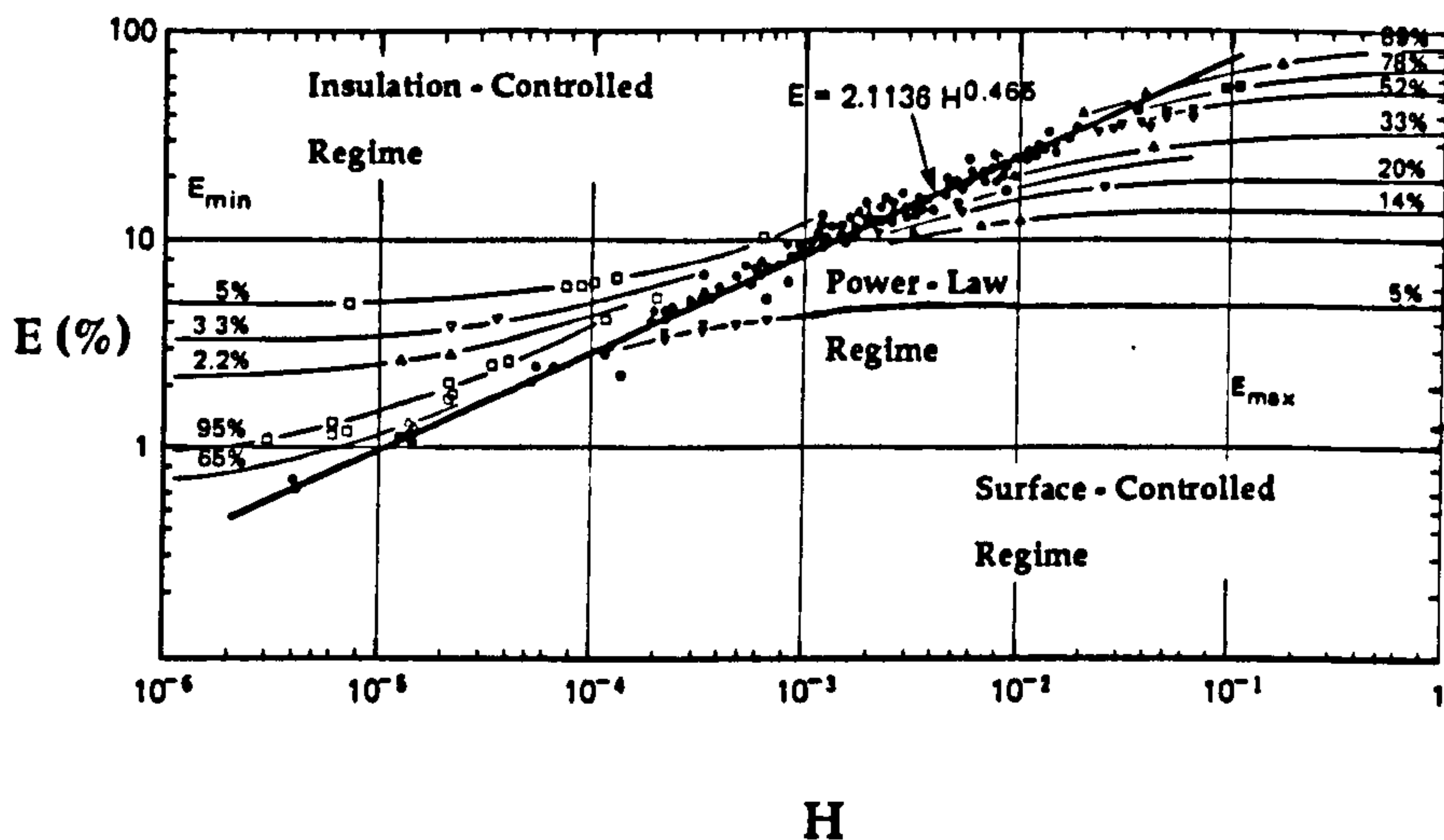
$$s = +/-1$$

$$c = \text{fitted constant} = 2.1136$$

$$n = \text{fitted constant} = 0.4650$$

$$H = \text{dimensionless parameter}$$

Firm top and bottom limits ( $E_{\max}$  and  $E_{\min}$  respectively) to the best estimate of the systematic error  $E$  may also be defined. In the case of  $E_{\max}$  the error involved is equal to the ratio of the effective HFS resistance to the surface resistance [the effective resistance is the sum of the series thermal resistance of the HFS alone + the thermal contact resistance between the HFS and the substrate + (the total thermal surface resistance over the HFS - the total thermal surface resistance over the surrounding area)]. In the case of  $E_{\min}$  the error involved is simply the resistance ratio of the HFS to that of the total resistance of the wall structure.



Three operating regimes are defined :-

- Power Law Regime — Comprising the points which fall on or about the heavy black line.
- Insulation-Controlled Regime — Comprising the points to the left of the heavy black line, and which are asymptotic towards  $E_{min}$ .
- Surface-Controlled Regime — Comprising the points to the right of the heavy black line, and which asymptotic towards  $E_{max}$ .

where

$E$  is the best estimate of the systematic error for a particular wall construction and  
 $H$  is a dimensionless parameter based on parametric studies

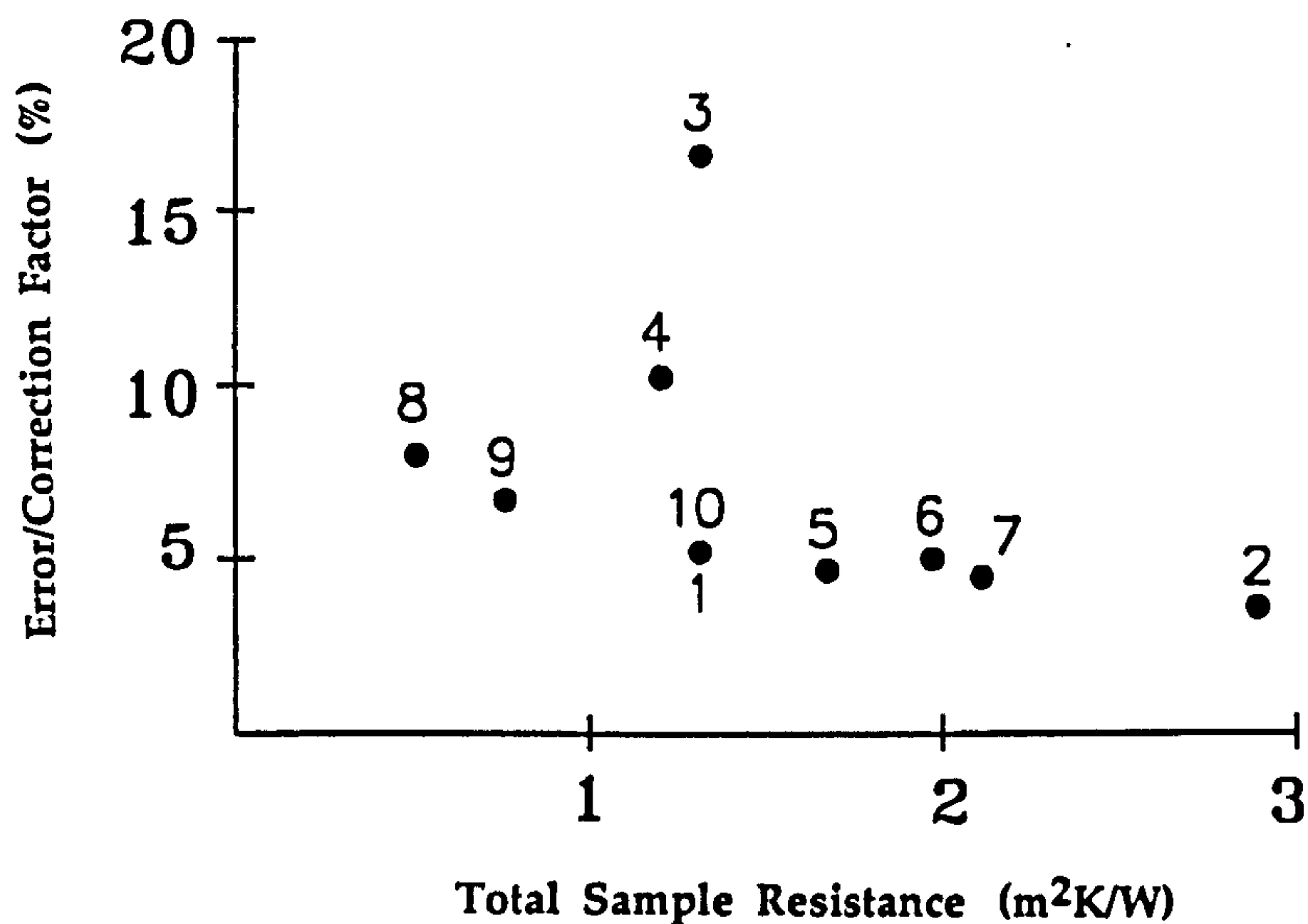
**Fig. 5.6:**

*Correlation of predicted error,  $E$ , with dimensionless parameters  
 (After Trethowen - 1986)*



Application in the present study

Trethowen's model was applied to a range of ten different wall constructions (the majority were investigated in the present study using the TNO HFSs - Table 5.4). The results are shown in Fig. 5.7.



**Fig. 5.7:**  
*Correction factors due to the attachment of HFSs on the wall surface  
for ten different wall constructions by applying the Trethowen model*

The largest error/correction factor of 17% is for wall 3 where no silicone grease is used between the HFS and the wall surface. The effect of not using silicone grease as a medium between the HFS and the wall surface in order to improve the thermal contact can easily be seen by comparing wall 3 to wall 1 which have the same construction. There is substantial difference in the correction factors when a medium is not used. The presence of an air-gap underneath the sensor may also introduce a considerable error. The correction factor varies between 3.6% (wall 2) and 10.23% (wall 4) for practical constructions. The correction is mainly determined by the substrate of the inner leaf. This can be seen by comparing walls 1 and 4. The wall resistance also has an influence on the final error value and this can be seen by comparing walls 1 and 2. In other words, when some form of insulation exists in the cavity, the estimated error becomes increasingly smaller, as the thickness of the insulation increases. Walls 5 to 10 are indicative examples of different constructions.

Finally, Fig. 5.7 indicates that there is a large scatter, consequently no global correction can be applied and every wall construction has to be corrected on an individual basis.

No.	OUTER LEAF	CAVITY	INNER LEAF	TOTAL WALL RESISTANCE (m <sup>2</sup> K/W)	ERROR E (%)
1	Brick	65 mm	Lightweight block + 13 mm plaster	1.315	5.20
2	Brick	65 mm fully filled with blown mineral wool	Lightweight block + 13 mm plaster	2.898	3.60
3	Brick	65 mm	Lightweight block + 13 mm plaster (no silicone grease was used)	1.315	16.67
4	Brick	65 mm	Lightweight block (no plaster)	1.205	10.23
5	Brick	60 mm	"Polyblock" + 13 mm plaster	1.670	4.66
6	Brick	60 mm fully insulated with blown mineral wool	Brick + 19 mm plaster	1.973	5.00
7	Timber frame 10mm plywood (Environmental chamber)	100 mm partially filled with 50 mm WALLMATE insulation board	13 mm Gypsum plasterboard only	2.113	4.46
8	Brick	65 mm	Heavyweight block + 13 mm plaster	0.510	8.00
9	Brick	65 mm	Lightweight block + 13 mm plaster	0.762	6.7
10	Brick	65 mm	Super-lightweight block + 13 mm plaster	1.315	5.2

**Table 5.4:**  
*Errors/heat flow distortion correction factors for different wall constructions calculated according to Trethowen's model.*



### 5.1.3 Boundary conditions

There is a substantial body of literature to indicate that the boundary conditions vary in space and time. The extent to which the boundary conditions may vary over the internal surface of a wall can clearly be seen in Fig. 2.8 - chapter 2. However, what is important in heat flow measurements, is not the temporal variability but the difference in boundary conditions experienced by the wall surface and the sensors. Ideally spatially uniform boundary conditions must extend over an area large enough to ensure 1D heat flow. A number of authors have commented on possible differences between the surface heat transfer conditions over the HFS, and over the remaining undisturbed surface (e.g. Flanders - 1985, Trethowen - 1985, 1986). The following conditions are examined in the context of heat flow measurements:

- (1) the convective component: the heat flow is laminar over the wall surface and trips to turbulent over the sensor
- (2) the radiation environment - longwave component: matching of the sensor's emissivity with that of the wall surface
- (3) the radiation environment - shortwave component: matching of the sensor's solar absorptivity with that of the wall surface.

The energy exchange which is taking place between the wall and the room environment has convective, longwave and shortwave radiation components (chapter 2). In order to determine the influence of the change in boundary conditions, the following model can be applied. The energy exchange for the wall is given by:

$$Q/A = h_c (T_a - T_w) + \epsilon \sigma (T_e^4 - T_w^4) + \alpha_s (Q/A)_{sw} \quad (5.1)$$

where

$Q/A$	= heat flux ( $W/m^2$ )
$h_c$	= convection heat transfer coefficient ( $W/m^2K$ )
$T_a$	= air temperature ( $^{\circ}C$ )
$T_w$	= external wall surface temperature ( $^{\circ}C$ )
$T_e$	= mean temperature of the surrounding environment [mean temperature of the 5 other surfaces in the room] ( $^{\circ}C$ )
$\epsilon$	= emissivity
$\sigma$	= Stefan-Boltzmann constant = $5.7 \times 10^{-8}$ ( $W/m^2K^4$ )
$(Q/A)_{sw}$	= flux from shortwave diffused radiation
$\alpha_s$	= absorptance of short wavelengths

subscript  $_{sw}$  = shortwave source, (solar radiation)

The heat flow conducted through the HFS develops a temperature difference across the thickness of the sensor body. This temperature difference causes the sensor to experience a different heat exchange from that of the surface on which it is mounted.

Therefore:  $(\Delta Q/A) = (Q/A)_w - (Q/A)_s$  (5.2)

where  $(\Delta Q/A) =$  difference in heat flow

$(Q/A)_w =$  heat flow through the wall

$(Q/A)_s =$  heat flow through the sensor

Hence, if Eq. (5.2) is expressed in terms of (5.1):

$(\Delta Q/A) =$  difference in the convective component +  
+ difference in the radiative (longwave) component +  
+ difference in the radiative (shortwave) component

$$(\Delta Q/A) = h_{cw} (T_a - T_w) - h_{cs} (T_a - T_s) +$$

$$+ \sigma [\epsilon_w (T_e^4 - T_w^4) - \epsilon_s (T_e^4 - T_s^4)] +$$

$$+ (\alpha_{sw} - \alpha_{ss}) * (Q/A)_{sw} \quad (5.3)$$

where  $h_{cw} =$  convective htc for the wall  
 $h_{cs} =$  convective htc for the sensor  
 $\epsilon_w =$  emissivity of the wall  
 $\epsilon_s =$  emissivity of the tape material covering the sensor  
 $\alpha_{sw} =$  solar absorptivity of the wall surface  
 $\alpha_{ss} =$  solar absorptivity of the tape material covering the sensor

A HFS on this surface will also exchange heat with the ambient environment at a sensor surface temperature  $T_s$ , where

$$T_s = T_w + \Delta T_s \quad (5.4)$$

where  $\Delta T_s$  is the temperature drop through the thermal resistance of the sensor and its mounting on the surface.



By substituting Eq. (5.4) into (5.3)

$$\begin{aligned} (\Delta Q/A) = & [(T_a - T_w) * (h_{cw} - h_{cs}) + h_{cs} \Delta T_s] + \\ & + \sigma [(\epsilon_w - \epsilon_s) * (T_e^4 - T_w^4) + 4 \epsilon_s T_w^3 \Delta T_s] + \\ & + (\alpha_{sw} - \alpha_{ss}) * (Q/A)_{sw} \end{aligned} \quad (5.5)$$

Eq. (5.5) expresses the limits of the variability of the boundary conditions across the surface of the wall between the HFS and the immediate wall.

### Convection

In the course of a heat flow measurement convective heat exchange occurs between the internal surface of the building envelope and the surrounding air. The following three conditions are possible:

- (1) the flow is laminar over the wall surface and the HFS during the test
- (2) the flow is turbulent over the wall surface and the HFS during the test
- (3) the flow is laminar over the wall surface and trips to turbulent over the HFS during the test, causing the sensor to record more heat flux than that occurring on the surrounding wall surface.

The worst case condition is obviously (3) and it is the one of interest for the present study. Two points are of importance at this stage:

- (a) How likely is condition (3) to occur during the measurement period?

Certain precautions must be taken in order to prevent condition (3) from happening, such as, placing tape over the sensor in order to smooth out the flow of air and prevent rapid transition of the flow. Even if the flow trips during the measurement period, it is unlikely to apply over the full test duration due to the changing boundary conditions.

- (b) what is the magnitude of the convective component under condition (3)?

An indication of the magnitude of the effect for the worst case condition can be given from the convective component of Eq. 5.5.

In free convection the product ( $Pr * Gr$ ) serves as a criterion of turbulence, the exact value depending on the geometric configuration. For the flow to change from laminar to turbulent in a vertical plate the Ra number [Rayleigh number - ( $Pr * Gr$ )] must be about  $10^9$  (Rogers and Mayhew - 1980). It is reasonable to assume a temperature difference in the indoor boundary layer ( $\Delta T_a$ ) of  $2.5^\circ\text{C}$  or  $1^\circ\text{C}$ . In practice, a poorly insulated wall construction will have a T value of approximately  $2 \text{ W/m}^2\text{K}$  which will correspond to heat flows of  $15 - 20 \text{ W/m}^2$  registered by the HFS. For a typical  $10 \text{ K}$  temperature drop across the wall the following expression may be applied:

$$\Delta T_a = \frac{R_{si}}{R_{wall}} * \Delta T = 2.4 \text{ (K)}$$

where  $\Delta T_a$  is the temperature difference in the indoor boundary layer (K)  
 $R_{si}$  is the internal surface resistance =  $0.120 \text{ (m}^2\text{K/W)}$   
 $R_{wall}$  is the overall resistance of the wall (including surface resistances)  
=  $0.5 \text{ (m}^2\text{K/W)}$  for a T value of  $2 \text{ (W/m}^2\text{K)}$   
 $\Delta T$  is the temperature drop across the wall construction =  $10 \text{ (K)}$

If the same is applied to a well insulated wall construction which has a T value of approximately  $0.6 \text{ W/m}^2\text{K}$ , the corresponding heat flows registered by the HFS are of the order of  $4 - 8 \text{ W/m}^2$ . For a typical  $10 \text{ K}$  temperature drop across the wall therefore the above expression may be applied with the result of  $\Delta T_a = 0.7 \text{ (K)}$ .

The following expressions were used in order to calculate the htc's (chapter 2 - section 2.3.1):

$$h_{cw} = 1.42 (\Delta T_a / L)^{1/4} \quad (\text{for laminar flow}) \quad (5.6)$$

$$h_{cs} = 1.31 (\Delta T_a)^{1/3} \quad (\text{for turbulent flow}) \quad (5.7)$$

Hence, by substituting values in the convective component of Eq. (5.5),

$$[(T_a - T_w) * (h_{cw} - h_{cs}) + h_{cs} * \Delta T_s]$$

where

$\Delta T_a = (T_a - T_w) =$  temperature difference in the indoor boundary layer (K)

$h_{cw} =$  htc over the wall surface - laminar ( $\text{W/m}^2\text{K}$ )

$h_{cs} =$  htc over the sensor surface - turbulent ( $\text{W/m}^2\text{K}$ )

$\Delta T_s =$  temperature difference between the wall and the sensor surface (K)

=  $Q$  (heat flow through the sensor) \*  $R$  (resistance of the HFS =  $0.012 \text{ m}^2\text{K/W}$ )

$Q =$  the standard internal htc ( $8.1 \text{ W/m}^2\text{K}$ ) \*  $\Delta T_a$  ( $2.5$  or  $1 \text{ K}$ )



Table 5.5 results:

$\Delta T_a$	2.50	1.00
$h_{cs}$	1.78	1.31
$h_{cw}$	1.44	1.15
$\Delta T_s$	0.25	0.10
Convective component (W/m <sup>2</sup> ) [Eq. 5.5]	-0.40	-0.03

**Table 5.5:**  
*Difference in convective heat flux registered by the HFS and the surrounding wall surface when the htc is laminar over the surrounding wall surface and turbulent over the sensor.*

Therefore, for the worst case condition (3) the sensor registers an additional convective heat flux - of 0.40 W/m<sup>2</sup> for a  $\Delta T$  of 2.5 °C and 0.03 W/m<sup>2</sup> for a  $\Delta T$  of 1 °C - more than the surrounding surface.

**Longwave radiation**

Inter-surface longwave radiation is a function of the prevailing surface temperatures, the emissivity of each surface, the extent to which the surface pair are in visual contact, and the nature of the surface reflection, specular or diffuse. Table 5.6 indicates the emissivities of the surfaces used in the present study.

Surface	Emissivity
HFS covered by masking tape	0.85 - 0.95
Wall surface	0.85 - 0.95

**Table 5.6:**  
*Emissivity values for surfaces employed in the present study*

In order to evaluate the radiative component of Eq. 5.5 for the three conditions regarding the emissivities of sensor and wall surface that may be encountered in an enclosure, extreme values are used from Table 5.7.

$\epsilon_w$	$\epsilon_s$
0.85	0.95
0.95	0.85
0.90	0.90
<p><b>Table 5.7:</b></p> <p><i>Extreme values used for wall and HFS surface emissivities (<math>\epsilon_w</math> and <math>\epsilon_s</math> respectively)</i></p>	

The mean enclosure temperature  $T_e$  (the mean temperature of the five other surfaces in the room) is assumed to be greater than the external wall surface temperature where the HFS is attached. It is reasonable to assume temperature differences of 1 K and 0.5 K in the radiation environment of an enclosure which may be taken along with corresponding temperature differences between the sensor and the wall surface of 0.1 and 0.05 K respectively.

Hence, by substituting values in the radiative (longwave) component of Eq. 5.5:

$$\sigma [(\epsilon_w - \epsilon_s) * (T_e^4 - T_w^4) + 4 \epsilon_s T_w^3 \Delta T_s]$$

where:

- $\sigma$  =  $5.7 * 10^{-8}$  (W/m<sup>2</sup>K<sup>4</sup>)
- $\epsilon_w$  = emissivity of the wall surface
- $\epsilon_s$  = emissivity of the tape covering the sensor
- $T_e$  = temperature of the surrounding surfaces (K)
- $T_w$  = internal wall surface temperature (20 + 273 = 293 K)
- $\Delta T_e$  = temperature difference in the radiation environment of a room enclosure (K)
- $\Delta T_s$  = temperature difference between the wall surface and the sensor (K)

Table 5.8 results:



$\Delta T_e$	1.00	0.50
$\epsilon_w$	0.85	0.85
$\epsilon_s$	0.95	0.95
$T_e$	$21 + 273 = 294 \quad (T_w = 293)$	293.5 $(T_w = 293)$
$\Delta T_s$	0.10	0.05
Radiative component (longwave) (W/m <sup>2</sup> ) [Eq. 5.5]	-0.03	-0.015
<b>Table 5.8 (a):</b> <i>Additional radiative heat flux registered by the HFS when <math>\epsilon_s &gt; \epsilon_w</math></i>		

$\Delta T_e$	1.00	0.50
$\epsilon_w$	0.95	0.95
$\epsilon_s$	0.85	0.85
$T_e$	$21 + 273 = 294 \quad (T_w = 293)$	293.5 $(T_w = 293)$
$\Delta T_s$	0.10	0.05
Radiative component (longwave) (W/m <sup>2</sup> ) [Eq. 5.5]	+1.064	+0.530
<b>Table 5.8 (b):</b> <i>Additional radiative heat flux registered by the HFS when <math>\epsilon_s &lt; \epsilon_w</math></i>		

$\Delta T_e$	1.00	0.50
$\epsilon_w$	0.90	0.90
$\epsilon_s$	0.90	0.90
$T_e$	$21 + 273 = 294 \quad (T_w = 293)$	293.5 $(T_w = 293)$
$\Delta T_s$	0.10	0.05
Radiative component (longwave) (W/m <sup>2</sup> ) [Eq. 5.5]	+0.520	+0.260
<b>Table 5.8 (c):</b> <i>Additional radiative heat flux registered by the HFS when <math>\epsilon_s = \epsilon_w</math></i>		

Table 5.8 indicates the difference in radiative heat flow between the sensor and the surrounding wall surface, depending on the emissivities and the surface temperatures at a given radiation environment. The resulting values in Table 5.8 form an additional radiative heat flux which causes the HFS to register more or less than the surrounding wall surface. The plus sign may be taken as an increase to the heat flow through the surrounding wall surface by that amount and the minus sign as a decrease.

Any combination of the emissivities for the wall/sensor system will introduce a systematic error, the magnitude of which will depend upon the mismatch.

Even where the surface emissivities are matched exactly (Table 5.8 - condition c), there is still a difference in heat flow introduced due to the higher surface temperature of the sensor. When the emissivity of the sensor is higher than that of the wall (Table 5.8 - condition a), this partly compensates for the increased temperature of the sensor, whereas when the emissivity of the sensor is below that of the wall (Table 5.8 - condition b), then the difference in heat flow is increased because the two effects amplify each other. Therefore, when matching emissivities, it would appear to be desirable to have a lower emissivity on the wall.

### **Shortwave (solar) radiation**

What is of importance in field measurements, is the difference in solar radiation absorbed by the wall surface and the HFS. It is reasonable to assume that both the wall and the HFS are in fact subjected to the same amount of reflected solar radiation. The main issue therefore is the difference between the solar absorptivities of the two surfaces and the magnitude of the shortwave incident on the surface of the wall, in other words what is the amount of shortwave energy falling on the wall and the HFS?

Johannesson (1979), recommended that the sensor should have the same absorptance as the surface to which is applied, in order to avoid spurious influences from shortwave radiation.

Flanders and Marshall (1982), in their field measurements shielded the HFS which was taped on the internal wall surface with a sheet of paper, assuming "the paper cover to have about the same absorptance as the wall paint so that the sensor would absorb any radiant heat in the same way as the wall."

For the calculation of available solar gain through windows, information is required on the irradiation of vertical surfaces. Solar irradiation varies with locality, partly due to changes in latitude and partly to the different sky conditions prevailing (CIBSE Guide - Section A2).



The difference in solar energy  $\Delta I_s$  is given by:

$$\Delta I_s = I_s * (\alpha_{sw} - \alpha_{ss})$$

where  $I_s$  = intensity of solar radiation  
 $\alpha_{sw}$  = solar absorptivity of the wall surface  
 $\alpha_{ss}$  = solar absorptivity of the tape material covering the sensor

It may be estimated as follows:

$$I_s = \frac{I_{dv} * \text{hrs/day} * A_g * T_e}{A_T} = 0.055 \text{ W/m}^2 \quad (5.8)$$

where:  $I_{dv} = 10 \text{ (W/m}^2\text{)}$  = diffused cloudy or clear solar long term radiation  
on a vertical surface (Table A2.27, Section A2 -  
CIBSE Guide)

$\text{hrs/day} = 24 \text{ (hrs)}$  = is used if the long term average is to be calculated

$A_g = 0.60 \text{ (m}^2\text{)}$  = glazing area. The sites investigated had a north  
facing window of approx. dimensions  $0.6 * 1\text{m}$

$T_e = 0.80$  = transmittance factor for clear float glass, 6mm  
(British Standards - DD67: 1980)

$A_T = 86 \text{ (m}^2\text{)}$  = total internal surface of a typical room of  
cuboid dimensions (side of 3.8m)

The difference  $\Delta I_s$  between the HFS and the wall surface is given by:

$$\Delta I_s = I_s * (\alpha_{sw} - \alpha_{ss})$$

Assuming that the solar absorptivity values of the tape covering the sensor and the wall surface can be matched to within  $\pm 0.1$ , it follows that:

$$I_s * (\Delta \alpha_s) = 0.005 \text{ (W/m}^2\text{)}$$

where  $\Delta \alpha_s = \pm 0.1$  (Table 5.9)

Surface/description/composition	Solar (shortwave) absorptivity ( $\alpha_s$ )
Black paint (Parsons)	0.98
Black (chrome) metal	0.87
Brick, red (Purdue)	0.63
Concrete	0.60
White (acrylic) paint	0.26
White (zinc oxide) paint	0.16
<p><b>Table 5.9:</b>  <i>Solar absorptivity values (<math>\alpha_s</math>) for different surfaces</i>  <i>(Based on Incropera and DeWitt - 1985)</i></p>	

Therefore the maximum error expected from solar radiation is very small - of the order of 0.005 W/m<sup>2</sup>. In other words, the heat flow passing through the HFS is overestimated by the above value, being subjected to an additional amount of energy. However, a large proportion of this additional amount of energy is then reradiated back into the room because of the subsequent surface temperature increase, so it is reasonable to assume that the final error will be less.

#### 5.1.4 Overall error analysis

A number of systematic and random errors are involved in the field measurement process. The errors presented in Tables 5.10 to 5.12 only serve to provide an indication of the errors involved in a thermal transmittance field measurement under the worst possible conditions. A more precise analysis of the errors involved is only possible for a given wall construction, for a given transmittance value and by applying the unique conditions for the particular site.

The values detailed in the previous sections have to be examined as a component of the combined convective and radiative exchange and in the context of the overall difference/error between the heat flux registered by the HFS and the heat flux registered by the surrounding wall surface.

The errors attributed to the change in boundary conditions and to shortwave radiation are presented in Table 5.10 on an individual basis. The overall/combined error is presented in Table 5.11 which indicates that the larger error is resulting when the emissivity of the wall surface is greater than the emissivity of the sensor.



CONDITION		
<p>Change in convective component (W/m<sup>2</sup>)</p> <p>(laminar/turbulent)</p>	-0.40	-0.03
<p>Change in longwave component (W/m<sup>2</sup>)</p> <p>(mismatch of sensor/wall emissivities)</p> <p>[<math>\epsilon_s &gt; \epsilon_w</math>]</p> <p>[<math>\epsilon_s &lt; \epsilon_w</math>]</p> <p>(Temperature difference of HFS) [<math>\epsilon_s = \epsilon_w</math>]</p>	<p>-0.030</p> <p>+1.064</p> <p>+0.520</p>	<p>-0.015</p> <p>+0.530</p> <p>+0.260</p>
<p>Change in radiative component (shortwave)</p> <p>(mismatch of surface absorptance)</p>	+0.005	+0.005
<p><b>Table 5.10:</b></p> <p><i>Error resulting from variation in the boundary conditions</i></p> <p><i>- components are shown individually - (worst case condition)</i></p>		

Eq. 5.5 (W/m <sup>2</sup> )  (all components)	0.425	0.040	for $\epsilon_s > \epsilon_w$
	0.670	0.505	for $\epsilon_s < \epsilon_w$
	0.125	0.235	for $\epsilon_s = \epsilon_w$
<b>Table 5.11:</b> <i>Overall error resulting from variation in the boundary conditions</i> <i>- components are shown together - (worst case condition)</i>			

In the present study a typical heat flow value of between 6 and 10 W/m<sup>2</sup> was registered on average. Table 5.12 indicates the errors in percentage terms for an average heat flow through the wall fabric of 8 W/m<sup>2</sup> where it can be seen that for a smaller temperature difference in a room environment the errors are generally smaller than that for a larger temperature difference. In other words the influence of the parameters discussed above is considerably smaller for a better insulated wall.

When the errors are looked at on an individual basis they may seem large, which is not unexpected since there may be a large variation in the heat transfer coefficients which are very difficult to control during the measurement period.

However, the combined errors introduced seem to be of manageable proportions when they are considered in terms of the average heat flow through the wall fabric and when viewed in the context of the overall heat transfer problem.

Eq. 5.5  (Overall percentage error for all components)	5.30%	0.50%	for $\epsilon_s > \epsilon_w$
	8.40%	6.30%	for $\epsilon_s < \epsilon_w$
	1.60%	2.90%	for $\epsilon_s = \epsilon_w$
<b>Table 5.12:</b> <i>Overall error resulting from variation in the boundary conditions</i> <i>- components are shown together in percentage terms - (worst case condition)</i> <i>for an average heat flow of 8 W/m<sup>2</sup></i>			



## 5.2 Data processing errors

### Analogue to Digital (A/D) conversion

Readings taken by the Squirrel logger at regular intervals can be selected by the user to be either the instantaneous values at the time when the reading is taken, or to be average values. The recording interval is the interval between storage of one regular set of readings and the next. The scan interval is the interval between readings taken for averaging.

Inputs are scanned at the end of each scan interval and the average of the values obtained is stored at the end of each recording interval.

In the present study the recording interval was set to be 15 minutes. The scanning interval was set to be 3 seconds, consequently at the 15 minutes recording interval, the final reading is the average of 300 values. That applies to all the recording channels.

A/D conversion will introduce an error. The maximum error associated with a single reading is:

Temperature channels:  $0.12^{\circ}\text{C}$  for a temperature range of  $0^{\circ}\text{C}$  to  $40^{\circ}\text{C}$

Heat flow channels:  $0.08\% \times \text{Reading} + 20\mu\text{v}$

(Note that 1 measurement = 300 readings and that the above figures are for Squirrel loggers used in ambient temperature of 5 to  $45^{\circ}\text{C}$ , and do not include sensor errors.)

### Temperature Sensors

For a single temperature measurement the maximum error of  $0.12^{\circ}\text{C}$ , which is equivalent to approximately 6 standard deviations, gives a standard deviation of  $0.04^{\circ}\text{C}$  for 300 readings (Pentz and Shott - 1988).

Assuming that the A/D conversion is random within any measurement period of 15 minutes the standard deviation associated with the averaged value is considerably smaller:  
 $0.04 / \sqrt{300-1} = 2.31 \times 10^{-3}^{\circ}\text{C}$ .

Therefore the error in a single temperature reading due to A/D conversion may be considered negligible.

## Heat Flux Sensors

The Squirrel logger was set to record between the range 0 - 20mv. For a single heat flux measurement the maximum error of +0.036 mv, which is equivalent to approximately 6 standard deviations, gives a standard deviation of 0.012 mv for 300 readings (Pentz and Shott - 1988).

Assuming the A/D conversion is random within any measurement period of 15 minutes the standard deviation associated with the averaged value is considerably smaller:

$$0.012 / \sqrt{300 - 1} = 7 * 10^{-4} \text{ mv.}$$

Therefore the error in a single heat flux reading due to A/D conversion may be considered negligible.



### 5.3 Data analysis errors

**Analysis of temperature and heat flow data to evaluate the Thermal Conductance or Resistance value ( $\Lambda$  or R value)**

Several methods are used to recover the  $\Lambda$  or R values from the heat flow and temperature data. The problem that all methods face is that a steady state value must be recovered, from dynamic conditions data taking into account any change in the stored energy of the wall during the measurement period. They can be broadly classified into two main types:

In the first type, the thermal resistance value is obtained from:

$$R = \frac{\text{average difference between surface temperatures}}{\text{average heat flow}}$$
$$R = \Sigma \Delta T / \Sigma Q \quad (5.9)$$

This method which is usually referred to as the Averaging method, has found widespread adoption and it has been used successfully by a number of workers, such as, Flanders and Marchall (1982), Issacs and Trethowen (1985), McIntyre (1985), Roulet et al (1985). One of the implicit assumptions in the application of this particular method is that any change in the heat storage of the wall fabric is considerably less than the total heat which has passed through it during the monitoring period.

The second type is characterized by methods that take into account the thermal storage of the wall fabric and includes:

The method developed by Ahvenainen et al (1980), where field results were analysed by means of a computer program, which was based on a theoretical model of statistical treatment of the conductive diffusion equation. The method could be applied to data collected during the whole year. They mention for their method that:

"After each iteration cycle the program outputs  
the value of the largest time constant,  
the standard error of estimate of the heat fluxes,  
the standard error of estimate of the thermal conductance,  
the thermal conductance value" (Ahvenainen et al - 1980).

This particular method, was used by Roulet et al (1985) for longer measurement periods (up to 50 days), in addition to the Averaging method. Both methods gave "stable results in the same measurement time" for heavyweight wall constructions. In some cases the dynamic

method gave "reliable results in a shorter measurement time than the Averaging method". However, Anderson (1985), commenting on this method states that: "This approach did not prove successful for measurement periods of two or three days." In addition to the above, Ahvenainen et al, concluded that "the results are not favourable for the use of this method as a routine field test - method".

In the method discussed by Brown and Schuyler (1982), the resistance of the wall is derived as a function of its mean temperature. They mention that there is "one dominant delay period" between the two data sets of  $\Delta T$  and  $Q$  respectively. This period can be "determined by finding the delay that produces the maximum cross-correlation between the temperature difference and the heat flow". The heat flux is then adjusted in phase by that amount. Data from a seven day period were used to calculate thermal resistance values, by means of two different procedures, with and without thermal lag. The results indicated that in each case there is a common  $R$  value within a range of  $\pm 5\%$ . The method, however, is applicable mainly to lightweight structures.

Anderson (1985), proposed that changes in the mean daily temperature required a correction to be made if the structure under investigation has a significant thermal mass. This analysis technique provides the possibility of reducing measurement periods from several weeks to some days and is based on the following set of assumptions:

- "1. The external temperature varies in an approximately sinusoidal cycle with a period of one day.
2. The magnitude of the cycle is not usually fixed for several days in succession.
3. There may be a change in the mean daily external temperature over the course of the test, in such a case some of the recorded heat flux will be stored in, rather than passing through the wall.
4. The internal temperature will not usually be constant. Unless closely controlled the mean daily value is likely to change if the external temperature changes, and there may be a cycle associated with intermittent heating" (Anderson - 1985).

The assumptions outlined above approximate the conditions to which wall constructions are subjected to in practice.

The essential feature of the method is the introduction of two correction factors which take into account the thermal mass of the wall;  $F_i$  for the internal leaf, and  $F_e$  for the external leaf of the wall. Anderson proposed that instead of obtaining the best estimate of  $\Lambda$  from Eq. (5.9), it should be obtained from:



$$\Lambda \text{ value} = \frac{\Sigma Q - (F_i * \delta T_i + F_e * \delta T_e)}{\Sigma \Delta T} \quad (5.10)$$

where

$F_i$  = 0.333 pcl (for the internal leaf of the wall)

$F_e$  = 0.167 pcl (for the external leaf of the wall)

pcl = thermal capacity of wall per unit area

$\Sigma Q$  = integrated heat flux

$\Sigma \Delta T$  = integrated temperature difference

$\delta T_i$  = change in internal temperature since start of integration period

$\delta T_e$  = change in external temperature since start of integration period

Consequently, no correction is applied during the first 24 hours. In order to obtain a relatively smooth curve of the transmittance value against time, an adjustment is made at each reading by reference to the preceeding 24 hours.

The correction factors proposed are significant for walls having fairly large mass. They depend heavily on the temperatures recorded during the first 24 hours. If these are unrepresentative, the corrected function may not be constant with time. An essentially level trend should be sought in the graph representing the measurement period against the U value - Fig. 5.8 (Anderson - 1985).

One limitation of the method is that the construction of the wall must be known before the analysis is made as well as the thermal properties of the building materials so that an estimate may be made of the thermal capacity of the structure. Anderson quotes that "usually it is possible to do this to sufficient accuracy (e.g. +/-20%) for the purpose of the analysis, .....". However, these constructional drawings/information "are often not available and even if they are, are surprisingly often inaccurate" as McIntyre (1985) states, especially if the building concerned is relatively old. Fig. 5.9 indicates the sensitivity of the Anderson method to changes in thermal capacity. It is obvious that in doubtful circumstances, it is advisable to underestimate, rather than to overestimate the thermal capacity of the wall. A 50% overestimation of the thermal capacity results in a 20% higher value while a 50% underestimation results in only 5% increase.

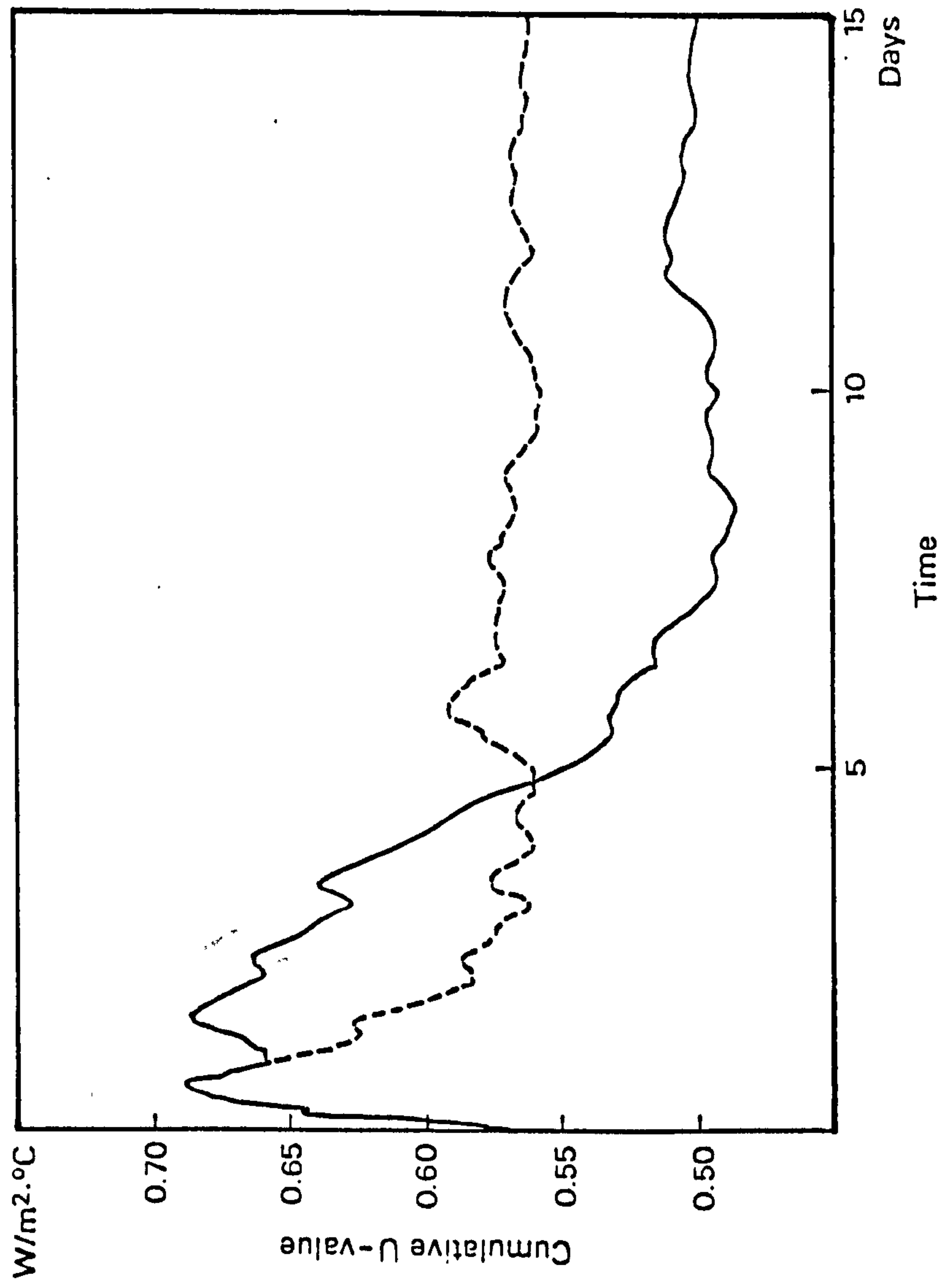


Fig. 5.8: Cumulative U value for brick wall with cavity fill: uncorrected for changes in internal and external temperature (solid line), and corrected (broken line) (After Anderson - 1985)



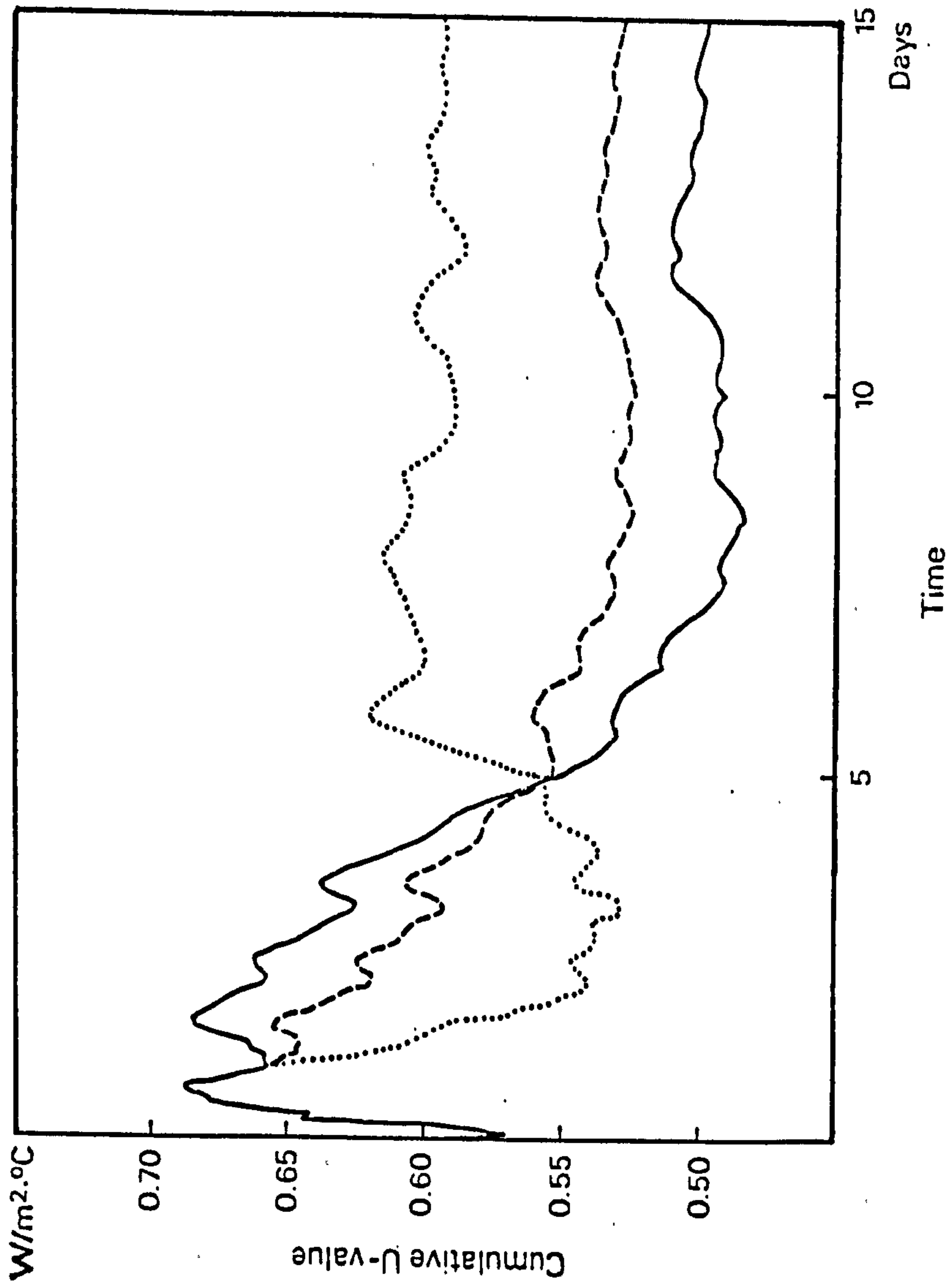


Fig. 5.9:

Cumulative U value data for double leaf brick with U.F. cavity fill.

Uncorrected (solid line), corrected with 50% underestimate of thermal mass (dashed line), and corrected with 50% overestimate of the thermal mass (dotted line)

(After Anderson - 1985)

### **5.3.1 Determination of the $\Lambda$ value and the number of monitoring days**

Two issues are of interest at this point. They are the determination of the appropriate  $\Lambda$  value and the determination of the number of monitoring days.

#### **(1) Determination of the appropriate $\Lambda$ value**

It is generally agreed that a 24hr integration period should be used for the steady state evaluation of the R or  $\Lambda$  value under field conditions. This is concluded from the references of several workers who carried out field measurements (Hedlin - 1980, Flanders and Marchall - 1982, Flanders - 1985, McIntyre - 1985, etc.).

#### **(2) Determination of the number of monitoring days**

From the literature review in chapter 3 - section 3.3.2, it is clear that monitoring periods range between 2 and 50 days. ASTM - STP 885 (1985) suggests that:

"If the thermal lag and the thermal resistance as a function of temperature are known, and, further, if the temperature difference across the wall is steadily between 15 and 20 K, at least, one 24hr period can be sufficient for testing wood-frame or masonry walls. On the other hand, if the thermal lag is unknown or if the temperature difference is less than 10 to 15 K, a much longer measuring period will be required. Finally, it should also be noted that, in cases where "there are concrete walls and roofs or when a moisture movement occurs in the building construction, the field testing period will be prolonged for a total of seven to ten days" (ASTM - STP 885 - 1985).

#### **The Averaging method**

Flanders and Marshall (1982), quote for their field measurements that "the duration of the measurement has marginal benefits on the accuracy of the measurement. Quadrupling the measurement time from 24 hours to 96 hours, increased the calculated value for R by 0.4%; a measurement time of 19 days increased the calculated value by 3% over the first day."

McIntyre (1985), discussed the sensitivity of the Averaging method to changes in the mean wall temperature. The consequences of a 1K change in the mean wall temperature and possible monitoring periods for a number of wall constructions are shown in Table 5.15. It is therefore, assumed, that for a change of more than 1K in the mean wall temperature, in case, for example, the internal temperature cannot be



closely controlled, the resulting error in heat flow and U value may be considerably > 5%. If this is the case, the number of monitoring days has to be increased.

	U-value (W/m²K)	Lag (h)	Specific heat per unit area (J/m²K)	Period (h)
Cavity brick/ lightweight block	1.0	8.1	$2.7 \times 10^5$	100
As above, + 50 mm cavity insulation	0.52	9.8	$2.7 \times 10^5$	200
Timber frame, 100 mm insulation, brick veneer	0.46	6.5	$2.1 \times 10^5$	160
Timber frame, 100 mm insulation, plywood sheath	0.50	2.4	$3.7 \times 10^4$	27
Double glazing	3.4	0.2	$1 \times 10^4$	1

The lag is the time for a temperature wave to travel from outside to inside of the wall. The final column shows the time period over which a change in mean wall temperature of 1K would produce an apparent error in heat flow and U-value of 5 per cent. This represents the worst case of all additional heat flux occurring at the inside surface.

**Table 5.13:**  
*U value and thermal capacity of typical structures*  
(After McIntyre - 1985)

**The Anderson method**

According to Anderson (1985) the number of monitoring days is dependent upon the accuracy needed to determine the  $\Lambda$  value. He provides means of estimating the desired accuracy by applying the expressions stated below:

**External temperature variation**

Based upon consideration of the variations in the cyclic external temperature profile, Anderson states that: "the limits of the  $\Sigma Q/\Sigma \Delta T$  range are to be regarded as the uncertainty band in the measurement, .....". The result is a damped sinusoidal oscillation of magnitude (peak to trough):

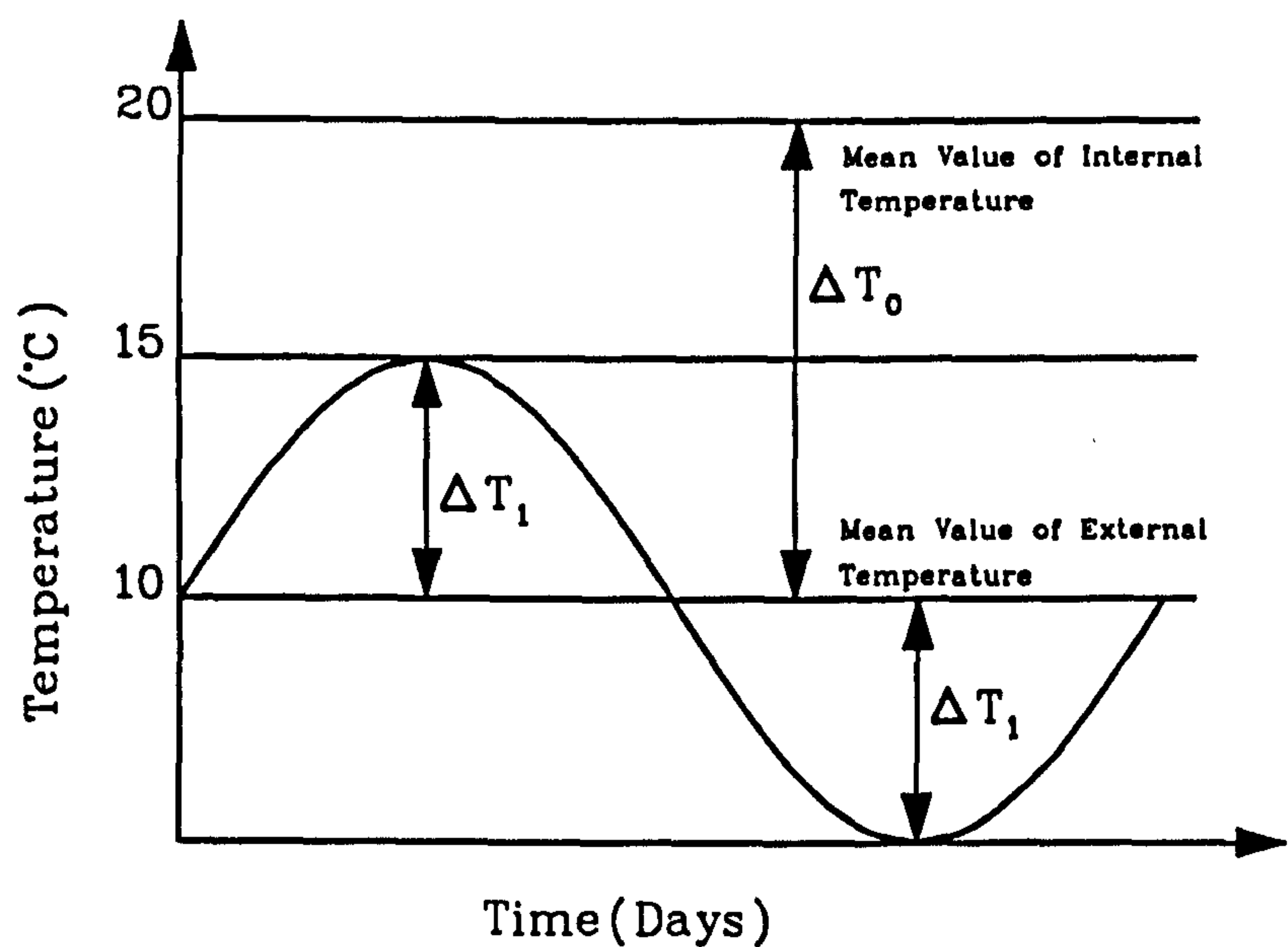
$$\pm 0.2 * \frac{\Delta T_1}{\Delta T_0} * \frac{1}{N} \qquad \text{(see also Fig. 5.10)}$$

where

- $\Delta T_1$  = amplitude of external temperature cycle
- $\Delta T_0$  = difference between the daily mean  
                  internal and external temperatures
- $N$  = number of days since the start of the integration period

The above expression can also be considered as the uncertainty band in the estimate of the thermal conductance value due to external temperature variation. Table 5.14 indicates clearly that as the number of monitoring days increases, the uncertainty resulting from the external temperature variation decreases. The conditions that apply are:  $\Delta T_1 = 5 \text{ }^\circ\text{C}$  and  $\Delta T_0 = 10 \text{ }^\circ\text{C}$ . The mean internal temperature was maintained at  $20 \text{ }^\circ\text{C}$ .

# External Temperature Variation



**Fig. 5.10:**  
*Uncertainty band for external temperature variation*  
*(Based on Anderson - 1985)*

Days	Uncertainty band for external temperature variation +/- (%)
5	2.00
8	1.25
10	1.00
12	0.83
14	0.71
18	0.55
25	0.40
40	0.25
<p><b>Table 5.14:</b>  <i>Uncertainty band on the external temperature variation with regard to the number of monitoring days</i>      <i>(Based on Anderson - 1985)</i></p>	



**Internal temperature variation**

The same applies for cyclic variations in the internal temperature. The admittance (Y) and transmittance (U) factors are included in this case. The result is again a damped oscillation of the ratio  $\Sigma Q/\Sigma \Delta T$  and the uncertainty band in the estimate of thermal transmittance due to internal temperature variation is given by:

$$+ \frac{1}{6} * \frac{Y}{U} * \frac{\Delta T_2}{\Delta T_0} * \frac{1}{N} \quad \text{(see also Fig. 5.11)}$$

where

$\Delta T_2$  = amplitude of internal temperature cycle

$\Delta T_0$  = difference between daily mean  
external and internal temperatures

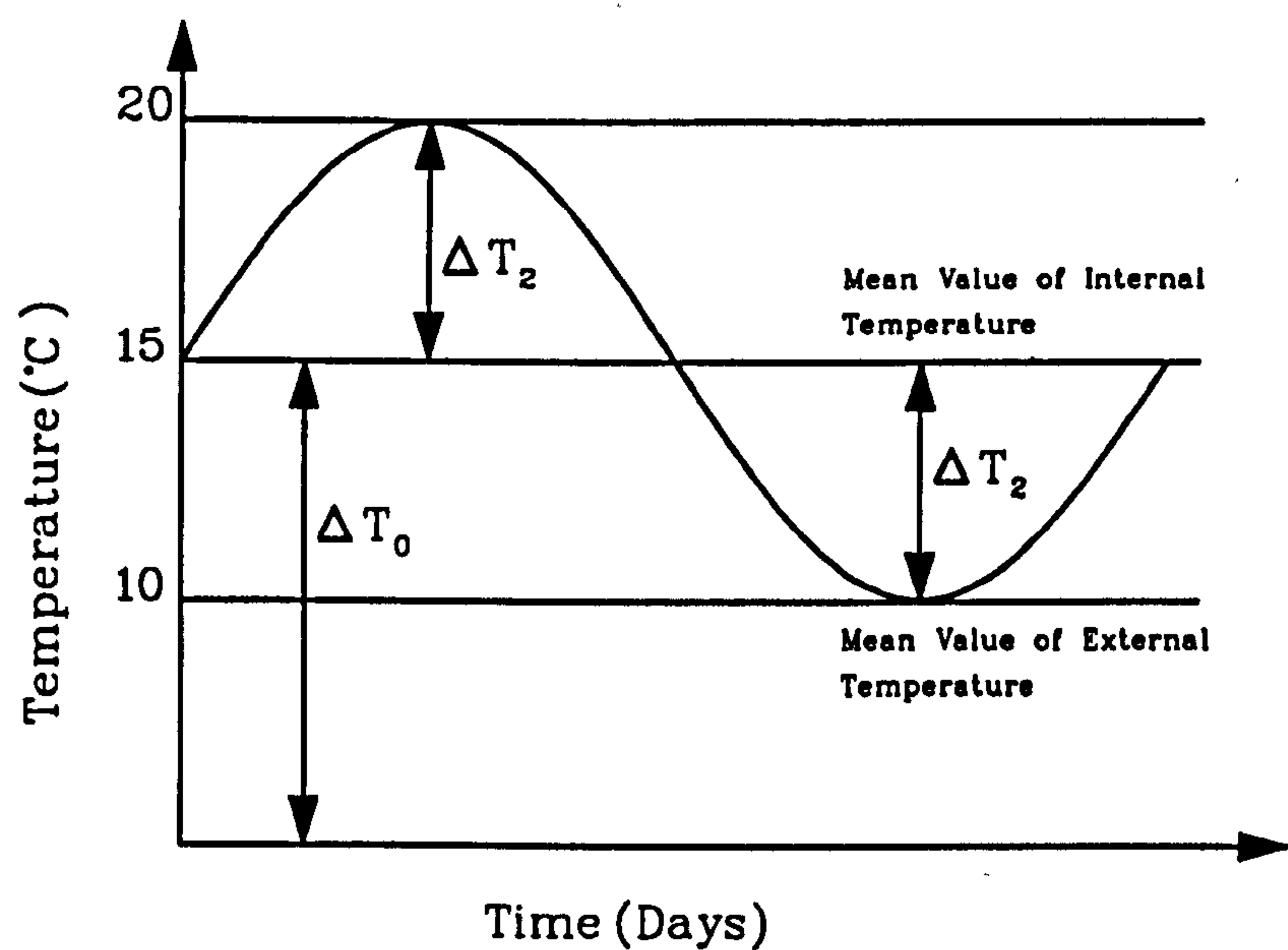
Y = admittance

U = U value

N = number of days since the start of the integration period

The above expression can also be considered as the uncertainty band in the estimate of the thermal conductance value due to internal temperature variation. Table 5.15 indicates clearly again that as the number of monitoring days increases, the uncertainty resulting from the internal temperature variation decreases. The conditions that apply are:  $\Delta T_2 = 5\text{ }^{\circ}\text{C}$  and  $\Delta T_0 = 10\text{ }^{\circ}\text{C}$ . The mean external temperature was maintained at  $10\text{ }^{\circ}\text{C}$ . The Table is applicable for a brick/insulated cavity/brick wall which has a U value of  $0.4\text{ W/m}^2\text{K}$  and a Y value of  $4.0\text{ W/m}^2\text{K}$ .

# Internal Temperature Variation



**Fig. 5.11:**  
*Uncertainty band for internal temperature variation*  
*(Based on Anderson - 1985)*

Days	Uncertainty band for internal temperature variation +/- (%)
5	17.00
8	10.42
10	8.33
12	6.94
14	5.95
18	4.63
25	3.33
40	2.00
<p><b>Table 5.15:</b>  <i>Uncertainty band on the internal temperature variation with regard to the number of monitoring days</i>      <i>(Based on Anderson - 1985)</i></p>	

In comparing Tables 5.16 and 5.17 respectively, it is obvious that the variation in the uncertainty band for the external temperature is considerably smaller than that of the internal. Therefore, the critical factor is the variation in the internal temperature, which must be controlled as closely as possible, during the monitoring period. Uncertainties also include the tolerance in the input parameters i.e. the physical dimensions and the thermal properties of the building materials used for the construction of the wall.

From the literature review it is apparent that two methods are appropriate for the present study: the widely used Averaging method, and the Anderson method. The Averaging method does not take into account changes occurring in the mean temperature of the wall fabric during the monitoring time, whereas the Anderson method does take into account the changes. In addition, Anderson's method takes into account external and internal periodic temperature variations about a sensibly mean value which can affect the integrity of the final U value (with respect to the number of monitoring days).

The interval time for recording data must be such, that high frequency fluctuations are averaged. In both methods the average  $\Lambda$  value from the last 24hrs is considered to be appropriate for retrieving the final transmittance value from the field data.

### 5.4 Conclusions

A number of errors are always involved in a thermal transmittance measurement, they cannot be eliminated and must be taken into account (Fig. 5.1). A summary of the errors involved is presented in Table 5.16. Some of the errors can be eliminated by adjusting the resulting value by an appropriate correction factor while others can be minimised by good practice.

Source of error	Magnitude of estimated error	Correction available
Calibration of sensors	14%	YES
Attachment of sensors on the wall surface	(typically) +5%	YES
Boundary conditions (including shortwave radiation)	< 10%	NO
Data processing errors (A/D conversion)	negligible	not required
Error involved in the analysis technique	6% (chapter 6 - section 6.7)	NO
<b>Table 5.16:</b> <i>Estimated errors in thermal transmittance measurements using HFSs</i>		



For any HFS and thermistor pair there are systematic errors introduced in thermal transmittance measurements. In the present study the maximum expected systematic error due to this combination is potentially  $\pm 7\%$ , a range of 14%. Where a number of measuring sets (1 set = 1 HFS and 2 mini-thermistors) is used, "relative calibration" between the sensors should be carried out and the final transmittance values be adjusted accordingly (section 5.1.1).

The attachment of sensors on the wall surface will inevitably create a distorted temperature and heat flux field in the surrounding area. However, it is possible to correct for this distortion. Trethowen's correlation in section 5.1.2 was found to be appropriate for this study and provided a good basis to estimate the correction factor resulting from the attachment of the sensors on the wall surface. This was found to be typically of the order of  $+5\%$  for plastered masonry constructions.

Variable boundary conditions during the monitoring period are expected to introduce an element of uncertainty into the measurement. An attempt was made to estimate the difference between the heat flow registered by the HFS and the heat flow registered by the surrounding wall surface for the worst case conditions which are outlined in section 5.1.3. The indications are that the combined errors resulting from the change in the boundary conditions and shortwave radiation are of manageable proportions ( $<10\%$ ). Worst case conditions are unlikely to occur on a continuous basis during the period of the measurement, in other words the errors involved may be even smaller. The exact nature of this type of error (whether it is systematic or random) is not known due to the highly variable behaviour of the conditions. Corrections are not available for this type of error.

The errors resulted from the A/D (analogue to digital) conversion were negligible (section 5.2).

A brief background of the two analysis techniques used in the present study was given in section 5.3. The only indication of the errors resulting from the analysis techniques is given from the field measurements in chapter 6 - section 6.7.1. An upper estimate of 6% is given of the variability introduced by changes in the material properties, changes in the environmental conditions at the particular point of measurement (the point at the internal surface of the wall where the sensors are attached) and to any differences introduced by the analysis technique.

An indication of the uncertainty involved in the determination of the  $\Lambda$  value with respect to the number of the monitoring days is given in section 5.3.1 and Appendix B where the analysis suggest that 4 monitoring days are enough to establish the conductance value of the wall within  $\pm 2.5\%$ .

**AN EVALUATION  
OF  
WALL PERFORMANCE**

**CHAPTER 6**

## **6.0 Introduction**

This chapter presents an investigation of the performance of different wall constructions. It seeks to integrate the theoretical performance of the wall with the results of a monitoring program in which measurements were made on 4 major wall types. The purpose is to gain a better understanding of how buildings/wall constructions perform in practice by:

- (i) broadly comparing the measured transmittance values with the theoretical values calculated according to the CIBSE Guide and a finite element model
- (ii) investigating the variability in the measured  $\Lambda$  values and
- (iii) the validity of the calculation methods

In order to sample a representative range of existing and new build constructions, examples of unfilled, partially filled and fully filled cavity walls were examined, each having a variety of inner and outer leafs. These have been categorized into 4 generic wall types and have been tabulated with regard to cavity fill (types that perform in a similar way) with a number of variations depending upon the nature of the inner leaf as follows:

### **"Polyblox" wall**

- (1) Cavity wall of brick outer and "Polyblox" inner leaf.

### **Unfilled cavity**

- (2) Cavity wall of brick outer and lightweight block inner leaf.

### **Partially filled cavity**

- (3) Partially filled cavity wall of brick outer and heavyweight (hollow) block inner leaf.
- (4) Partially filled cavity wall of brick outer and heavyweight (solid) block inner leaf.

### **Fully filled cavity**

- (5) Fully filled cavity wall of brick outer and lightweight block inner leaf (Retrofit).
- (6) Fully filled cavity wall of brick outer and inner leaf (Retrofit).



Table 6.0.1 indicates the number of positions measured on each wall construction type. For some wall types two figures appear. The main figure indicates the unique points (positions) of measurement. The figure in brackets indicates the number of multiple measurements.

### **6.0.1 Evaluation of wall performance**

The measured and theoretical performance of the wall is examined in order to enable comparisons between the measured and theoretical values to be drawn. The measured wall performance was determined using two methods, the Averaging method and the Anderson method (chapter 5 - section 5.3). One and three dimensional models were used for the calculation of the theoretical values (chapter 4). The values of the material properties used to calculate theoretical and measured results were either based on the provisional specifications/architectural drawings and Bills of Quantities available for the individual site or from site inspection when no drawings or specifications were available.

The presentation of the analysis is in the form of 6 case studies corresponding to the generic wall types. Each case study has a similar format to enable comparison between them and is structured into 5 specific sections as follows:

- (1) the measurement
- (2) description of the measurement
- (3) the measured performance of the wall
- (4) determination of the theoretical performance of the wall
- (5) comparison between the measured and theoretical transmittance values

Wall Type Case Study	A	B	C		D	
	1	2	3	4	5	6
	Brick/ Cavity/ "Polyblos"	Unfilled Cavity Brick/Cavity/ Lightweight Block	Partially Filled Cavity Brick/Partially Filled Cavity/Heavyweight Hollow Block	Brick/Partially Filled Cavity/Heavyweight Solid Block	Fully Filled Cavity Brick/ Retrofit Cavity Fill/Brick	Brick/ Retrofit Cavity Fill/ Lightweight Block
Location						
Freeman Hospital						TM 6 *
N. Tyneside Hospital (Residence)	TM 12(36)					
N. Tyneside Hospital (Psychiatry Block)		TM 5(13)				
Cramlington School			TM 6(16)			
Blyth School				TM 2(4)		
Morpeth (Till House)					8 *	
TOTAL Number of Measurements	12(36)	5(13)	6(16)	2(4)	8	6 GRAND TOTAL 39(69)

Explanation of the subscripts used in Table 6.0.1

TM = Thermal modelling has been applied for this particular wall type.

\* = These constructions were monitored before and after filling the cavity.

Lightweight blocks = blocks with density up to 750 Kg/m³

Heavyweight (medium) blocks = blocks with density between 750 and 1250 Kg/m³

Heavyweight (dense) blocks = blocks with density above 1250 Kg/m³

Table 6.0.1:

Distribution of measurements undertaken in the present study  
with respect to wall types and points/positions



## WALL TYPE A

### CASE STUDY 1

**CONSTRUCTION:** BRICK/CAVITY/"POLYBLOX"/PLASTER

**LOCATION:** NORTH TYNESIDE HOSPITAL  
DOCTORS RESIDENCE QUARTERS

**No. OF SITES:** 3

**SITE 1:** RESIDENCE - BLOCK 7

No. of unique measurement points: 4  
No. of multiple measurements: 12

**SITE 2:** RESIDENCE - BLOCK 9

No. of unique measurement points: 4  
No. of multiple measurements: 12

**SITE 3:** RESIDENCE - BLOCK 9

No. of unique measurement points: 4  
No. of multiple measurements: 12



**6.1     An evaluation of the performance of a brick/cavity/"Polyblox"/  
plaster wall   (Wall type A)**

"Polyblox" and "Polybond" (which is similar to "Polyblox" but instead of polyurethane, a layer of polystyrene is attached onto the block) would appear to represent simple and cost effective means of satisfying wall insulation requirements, imposed by the current Building Regulations. Such composite blocks are widely used, one of the major advantages being that an additional operation to form an insulation layer in the cavity is not required.

**6.1.0     The measurement**

Thirty-six measurements were undertaken at three Sites, Site 1, Site 2 and Site 3. The three Sites (two buildings), were part of a recently constructed residential area for practising doctors in the North Tyneside Hospital. The area comprised a total of seven, two storey flats. Two out of the total of seven buildings had the same wall construction (Blocks 7 and 9) and these were selected for inclusion within the study to give 3 different Sites as follows:

- Block 7 - Room 1:        Site 1
- Block 9 - Room 2:        Site 2
- Block 9 - Room 2:        Site 3

The "Polyblox" consists of a solid dense concrete block faced with an insulating layer of polyurethane which is fixed onto the surface of the block to create a fully composite unit (Boral Edenhall - 1987). In this particular case the architectural drawings/Bills of Quantities specify a block of 100mm thickness and an insulation layer which faces the cavity of 30mm thickness.

Table 6.1.1 gives the properties of the wall construction and a section of the wall is illustrated in Fig. 6.1.1 (all Tables and Figs. referring to wall construction details and measurement results are presented at the end of each section). The location of the measurement positions was determined by the availability of space on the wall surface and the requirement to place the sensors on a thermally uniform area of the wall. This was achieved by using the infrared camera so that thermal abnormalities on the wall could be established and avoided. Obvious defects were not apparent, close examination however revealed that the temperature profile on the wall surface was non-uniform. The mortar joints were not visible with the infrared camera. The reasons for this are discussed in the concluding section.

**6.1.1 Description of the measurement (Site 1)**

A series of 3 measurement periods was undertaken. Four HFSs were placed on the wall surface at the positions shown in Fig. 6.1.2. The HFS at position 4 was retained at the same position throughout the 3 monitoring periods. The measurement positions were all in the same north facing wall (Fig. 6.1.3). The rotation pattern of the HFSs is shown in Fig. 6.1.4. The duration of each monitoring period was approximately 14 days.

**The measured performance of the wall**

The measured wall performance is detailed in Table 6.1.2 and presented in a matrix form in Table 6.1.3.

The corrections applied to the measured values were; firstly, the term for the "relative" calibration of the HFSs and secondly a calculated correction of +5%, to allow for the heat flow distortion using Trethowen's correlation (chapter 5 - section 5.1.2).

Fig. 6.1.5 shows the temperature difference, the heat flux through the wall, the instantaneous  $\Lambda$  value, the Averaging and the Anderson cumulative  $\Lambda$  values for a representative measurement point (2nd monitoring period - Position 4 - Site 1).

The conductance values derived using the Averaging and the Anderson methods were found to be close together with the difference between any two values not exceeding 2.65% for any single measurement (Table 6.1.2). The Averaging method gave slightly lower estimates but this was less than 1%. Given the high correlation between the two values ( $R=0.9976$ ) in the following analysis, the Anderson values are taken as the appropriate measure of the wall transmittance.

Focusing on Position 4 where the HFS was retained at the same position throughout the 3 monitoring periods, the successive measurements were 0.9023, 0.8760 and 0.8739 respectively and indicate that the  $\Lambda$  value was relatively stable with time. The mean value was 0.8841 with a variation of less than 3.2% from the minimum value of 0.8739 to the maximum 0.9023 (Table 6.1.3).

Analysis of Variance was carried out for the 3 sensors that were rotated (S/Table 6.1.1). This indicates that the differences between the sensors and between the wall positions were significant at the 0.006 and 0.005 level respectively. There are significant differences in both; the performance of the wall at the selected positions and between the sensor sets.



The best estimate of the average wall performance at the 3 measurement positions (for the 3 rotating sensors) is 0.9459, 0.8755 and 0.7501 respectively with a mean value of 0.8572 and a standard error of the mean of 4%. There is a variation of some 40% between the upper and lower estimates of the measured wall performance (max. value - min. value/mean value).

There is some evidence to suggest that these measured values may be biased due to the significant differences between sensors. The expectation is that maximum difference between any two sensor sets would be less than 14% (chapter 5 - section 5.1.1), whereas in this case a difference of 21% is observed with sensor No. 65/mat 2 reading high.

The main effects of sensor and position explain most of the variation within the measurement set with the mean square of the residual or unexplained variance due to all factors other than the sensors and the positions being  $1.17 \times 10^{-3}$ . This gives an indication of the random error introduced by the attachment of the sensors on the wall and to all other random sources of variation in the measurement process, while the standard error associated with a single transmittance measurement is given by:

$$(\sqrt{\text{residual value}}/\text{mean sample value}) = \sqrt{1.17 \times 10^{-3}}/0.8572$$

and gives a value of 3.98% for 4 degrees of freedom.

SOURCE OF VARIATION	SUM OF SQUARES (10 <sup>-3</sup> )	DF	MEAN SQUARE (10 <sup>-3</sup> )	F	SIGNIF. OF F
Main Effects	116.56	4	29.14	24.981	0.004
Sensor	57.56	2	28.78	24.675	0.006 significant
Position	58.99	2	29.50	25.288	0.005 significant
Residual	4.67	4	1.17		
Total	121.22	8	15.15		
where F = mean square value/residual value					
<i>S/</i> Table 6.1.1: <i>Analysis of Variance for the 3 rotating sensors - Site 1 - Wall type A</i>					



**6.1.2 Description of the measurement (Site 2)**

A series of 3 measurement periods was undertaken. Four HFSs were placed on the wall surface at the positions shown in Fig. 6.1.6. The HFS at Position 4 was retained at the same position throughout the 3 monitoring periods. The heat fluxes were measured in the same north facing sitting room (Fig. 6.1.7). The rotation pattern of the HFSs is shown in Fig. 6.1.8. The duration of each monitoring period was approximately 14 days.

**The measured performance of the wall**

The measured wall performance is detailed in Table 6.1.4 and presented in a matrix form in Table 6.1.5.

The corrections applied to the measured values were; firstly, the term for the "relative" calibration of the HFSs and secondly a calculated correction of +5%, to allow for the heat flow distortion using Trethowen's correlation (chapter 5 - section 5.1.2).

Fig. 6.1.9 shows the temperature, the heat flux through the wall, the instantaneous  $\Lambda$  value, the Averaging and the Anderson cumulative  $\Lambda$  values for a representative measurement point (2nd monitoring period - Position 1 - Site 2).

The conductance values derived using the Averaging and the Anderson methods were found to be close together with the difference between any two values not exceeding 3% for any single measurement (Table 6.1.4). The Averaging method gave slightly lower estimates but this was less than 1.1%. Given the high correlation between the two values ( $R=0.9759$ ) in the following analysis, the Anderson values are taken as the appropriate measure of the wall transmittance.

Focusing on Position 4 where the HFS was retained in the same position throughout the 3 monitoring periods, the successive measurements were 0.8959, 0.9032 and 0.9025 respectively and indicate that the  $\Lambda$  value was highly stable with time. The mean value was 0.9005 with a variation of less than 0.8% from the minimum value of 0.8959 to the maximum of 0.9032 (Table 6.1.5).

Analysis of Variance was carried out for the 3 sensors that were rotated (S/Table 6.1.2). This indicates that the differences between the sensors and between the wall positions were significant at the 0.018 and 0.035 level respectively. There are significant differences in both; the performance of the wall at the selected positions and between the sensor sets.

The best estimate of the average wall performance at the 3 measurement positions (3 rotating sensors) is 0.8910, 0.8902 and 0.8305 respectively with a mean value of 0.8706 and a standard error of the mean of 1.7%. There is a variation of some 20% between the upper and lower estimates of the measured wall performance (max. value - min. value/mean value).

The main effects of sensor and position explain most of the variation (S/Table 6.1.2) within the measurement set with the mean square of the residual or unexplained variance due to all factors other than the sensors and the positions being  $0.42 \times 10^{-3}$ . This gives an indication of the random error introduced by the attachment of the sensors on the wall and to all other random sources of variation in the measurement process, while the standard error associated with a single transmittance measurement is given by:

$(\sqrt{\text{residual value}}/\text{mean sample value}) = \sqrt{0.42 \times 10^{-3}}/0.8706$   
and gives a value of 2.35% for 4 degrees of freedom.

SOURCE OF VARIATION	SUM OF SQUARES (10 <sup>-3</sup> )	DF	MEAN SQUARE (10 <sup>-3</sup> )	F	SIGNIF. OF F
Main Effects	17.95	4	4.49	10.709	0.021
Sensor	10.72	2	5.36	12.794	0.018 significant
Position	7.23	2	3.61	8.624	0.035 significant
Residual	1.68	4	0.42		
Total	19.63	8	2.45		
where F = mean square value/residual value					
S/Table 6.1.2: Analysis of Variance for the 3 rotating sensors - Site 2 - Wall type A					

### **6.1.3 Description of the measurement (Site 3)**

A series of 3 measurement periods was undertaken. This particular series of measurements was a repetition of the previous experiment at Site 2 in the same room/wall. The HFSs were placed in slightly different positions (a distance of 100 to 300mm from the original positions in different directions). In other respects the procedure remained the same. The Figs. referring to the location of the HFSs on the wall, as well as, the rotating pattern were all the same, as for Site 2. The duration of each monitoring period was approximately 14 days.

#### **The measured performance of the wall**

The measured wall performance is detailed in Table 6.1.6 and presented in a matrix form in Table 6.1.7.

The corrections applied to the measured values were; firstly, the term for the "relative" calibration of the HFSs and secondly a calculated correction of +5%, to allow for the heat flow distortion using Trethowen's correlation (chapter 5 - section 5.1.2).

Fig. 6.1.10 shows the temperature difference, the heat flux through the wall, the instantaneous  $\Lambda$  value, the Averaging and the Anderson cumulative  $\Lambda$  values for a representative measurement point (1st monitoring period - Position 1 - Site 3).

The conductance values derived using the Averaging and the Anderson methods were found to be close together with the difference between any two values not exceeding 3% for any single measurement (Table 6.1.6). The Averaging method gave slightly lower estimates but this was less than 0.05%. Given the high correlation between the two values ( $R=0.9630$ ) in the following analysis, the Anderson values are taken as the appropriate measure of the wall transmittance.

Focusing on Position 4 where the HFS was retained at the same position throughout the 3 monitoring periods, the successive measurements were 0.9870, 0.9296 and 0.9488 respectively and indicate that the  $\Lambda$  value was reasonably stable with time. The mean value was 0.9551 with a variation of less than 6% from the minimum value of 0.9296 to the maximum of 0.9870 (Table 6.1.7).

Analysis of Variance was carried out for the 3 sensors that were rotated (S/Table 6.1.3). This indicates that the differences between the sensors and between the wall positions were significant at the 0.011 and 0.022 level respectively. There are significant differences in both; the performance of the wall at the selected positions and between the sensor sets.



The best estimates of the average wall performance at the 3 measurement positions (3 rotating sensors) is 0.9530, 0.8520 and 0.9040 respectively with a mean value of 0.9030 and a standard error of the mean of 2.3%. There is also a variation of some 27.5% between the upper and lower estimates of the measured wall performance (max. value - min. value/mean value).

The main effects of sensor and position explain most of the variation (S/Table 6.1.3) within the measurement set with the mean square of the residual or unexplained variance due to all factors other than the sensors and the positions is  $0.66 \cdot 10^{-3}$ . This gives an indication of the random error introduced by the attachment of the sensors on the wall and to all other random sources of variation in the measurement process, while the standard error associated with a single transmittance measurement is given by:

$$(\sqrt{\text{residual value}}/\text{mean sample value}) = \sqrt{0.66 \cdot 10^{-3}}/0.9030$$

and gives a value of 2.85% for 4 degrees of freedom.

SOURCE OF VARIATION	SUM OF SQUARES (10 <sup>-3</sup> )	DF	MEAN SQUARE (10 <sup>-3</sup> )	F	SIGNIF. OF F
Main Effects	37.49	4	9.37	14.109	0.013
Sensor	22.21	2	11.10	16.714	0.011 significant
Position	15.29	2	7.64	11.504	0.022 significant
Residual	2.66	4	0.66		
Total	40.15	8	5.02		
where F = mean square value/residual value					
<p><i>S/Table 6.1.3:</i></p> <p><i>Analysis of Variance for the 3 rotating sensors - Site 3 - Wall type A</i></p>					

6.1.4 Comparison between the measured values for the 3 Sites

The measured values obtained from the 3 Sites, the random measurement errors, the differences between the sensors and the differences in the wall behaviour are examined in turn.

Random measurement errors

An indication of the long term stability of the wall performance and the variability introduced by all random processes in the measurement except for attaching the sensors on the wall can be obtained from an examination of the sensors that were retained at the same position at each of the three Sites. Consequently the values for each position/sensor combination for each time period were subject to a one way Analysis of Variance. S/Table 6.1.4 shows that the differences between the measured transmittance at each of the Sites was significant, i.e.

Site 1: 0.8841  
Site 2: 0.9005  
Site 3: 0.9551

}

with a mean of 0.9132

SOURCE OF VARIATION	SUM OF SQUARES (10 <sup>-3</sup> )	DF	MEAN SQUARE (10 <sup>-3</sup> )	F	SIGNIF. OF F
Main Effects	8.90	2	4.45	9.915	0.013
Posit/Sensor	8.90	2	4.45	9.915	0.013 significant
Residual	2.69	6	0.45		
Total	11.59	8	14.49		
where F = mean square value/residual value					
S/Table 6.1.4: Analysis of Variance for the 3 non-rotating sensors - Sites 1, 2 and 3 - Wall type A					

Given the detection of the significant differences between sensors found in the rotation experiments it is safe to conclude that the differences between the means are partly due to the different measurement positions and partly due to the different sensor sets used at each of the positions.

The interesting feature of this set of results is that the residual variance is a measure of all the random processes in the measurement except for attaching the sensors to the wall. The standard error of measurement for a single transmittance value being 2.32% in this particular case for 6 degrees of freedom. This gives an indication of the random error of measurement including:

- (1) changes in the convective and radiative environment
- (2) changes in the wall performance
- (3) the error involved in the analysis procedure
- (4) the long term stability of the wall

This is to be contrasted with the standard error of measurement where the sensors were rotated which also includes the variability introduced by fixing the sensors to the wall, namely:

Site 1: 3.98%

Site 2: 2.35%

Site 3: 2.85%

The pooled variance for these three sites gives a standard error of 3.1% (Edwards - 1969) which is marginally greater than that for the fixed sensor. It is interesting to note that from the chamber experiment the standard error was 2.1%.

S/Table 6.1.5 indicates the values for the random errors involved in a thermal transmittance measurement in both, the field and the laboratory. This is the standard error of estimate for a single transmittance measurement. As expected the random errors are increasing when measurements are taking place under field conditions and fixing is included.



	Field	Lab
All random errors including fixing	3.1%	2.1%
Random errors excluding fixing	2.3%	X
<b>S/Table 6.1.5:</b> <i>Random error associated with a single measurement of transmittance</i>		

### Differences between sensors

Evidence for differences between sensors was sought by examining the mean transmittance values for each sensor averaged over each of the 3 positions at each of the Sites during the rotation experiment.

The Analysis of Variance (S/Table 6.1.6) shows that while there were no differences in the average wall performance measured at each of the 3 Sites, there was a very large residual variance due to differences in sensor performance. This translates into a standard error of some 8.1%. Much of the variation can be traced to sensor 65 at Site 1 which gave consistently high readings. When this sensor is eliminated a reduced standard error of 5.4% results (S/Table 6.1.7). This can be interpreted as follows:

Where 1 sensor is used to measure the behaviour of the wall over 3 different positions the standard error of the mean wall performance due to the sensors alone is of the order of 5.4%. This is a measure of the variability introduced into the thermal transmittance measurement by the sensor. A measure of the "true" value could only be obtained if a precisely calibrated sensor had been used. In this case the error of the mean wall performance would have been 0%. However, where 3 sensors are used as in the rotation experiment the standard error is reduced to  $5.4/\sqrt{3} = 3.1\%$ .

SOURCE OF VARIATION	SUM OF SQUARES (10 <sup>-3</sup> )	DF	MEAN SQUARE (10 <sup>-3</sup> )	F	SIGNIF. OF F
Main Effects	3.33	2	1.67	0.331	0.730
Mean Wall Performance	3.33	2	1.67	0.331	0.730 not signif.
Residual	30.15	6	5.02		
Total	33.48	8	4.18		
where F = mean square value/residual value					
<i>S/</i> Table 6.1.6: <i>Analysis of Variance for the means of all sensors - Wall type A</i>					

SOURCE OF VARIATION	SUM OF SQUARES (10 <sup>-3</sup> )	DF	MEAN SQUARE (10 <sup>-3</sup> )	F	SIGNIF. OF F
Main Effects	12.71	2	6.36	2.896	0.146
Mean Wall Performance	12.71	2	6.36	2.896	0.146 not signif.
Residual	10.97	5	2.19		
Total	23.68	7	3.38		
where F = mean square value/residual value					
<i>S/</i> Table 6.1.7: <i>Analysis of Variance for the means of all sensors excluding No. 65 - Wall type A</i>					

Differences in wall behaviour

The differences in wall performance were examined using the data set referring to the rotated sensors (disregarding sensor No. 65 which reads high).

The Analysis of Variance given in S/Table 6.1.8 is for the mean value measured by 3 sensors at each Position at each Site. The differences between each Site are not significant but there is a substantial residual error variance which translates into a standard error of 7.7%. This can be interpreted as follows:

Where the mean performance of a single position on the wall is determined by 3 sensors the standard error in wall performance is 7.7%. If the average value at each position is taken to be a reasonable reliable estimate of the wall performance at that position then the standard error gives an indication of the variability of the wall performance. Where the measurement is made over 9 positions as in this case the mean wall performance is determined with a standard error of 2.56% ( $7.7 / \sqrt{9}$ ).

SOURCE OF VARIATION	SUM OF SQUARES (10 <sup>-3</sup> )	DF	MEAN SQUARE (10 <sup>-3</sup> )	F	SIGNIF. OF F
Main Effects	16.42	2	8.21	1.872	0.233
Mean Wall Performance	16.42	2	8.21	1.872	0.233 not signif.
Residual	26.31	6	4.38		
Total	42.73	8	5.34		
where F = mean square value/residual value					
<i>S/Table 6.1.8:</i> <i>Analysis of Variance for all positions excluding sensor No. 65 -</i> <i>Sites 1, 2, 3 - Wall type A</i>					

The mean of all the values recorded by the rotating sensors at the 3 Sites and excluding sensor No. 65 at Site 1 is 0.8689 and may be taken as the best estimate of the average measured wall performance for this particular type of construction. Consequently, the measured value of 0.87 is to be compared with the theoretical values.



### 6.1.5 Determination of the theoretical performance of the wall

Estimating the heat flow through a "Polyblox" wall is highly complex due to its composite nature. Different models may be used to represent the performance of the wall but in each case the result depends upon the initial assumptions made concerning material properties, dimensions and htc's. To give an insight into the behaviour the following models were used to calculate the theoretical performance of the wall.

- (1) manufacturers model
- (2) the CIBSE area weighted model
- (3) finite element model

#### Manufacturers model:

The buildings in question were completed in February 1988 and manufacturers published data specify a wall U value of  $0.60 \text{ W/m}^2\text{K}$  "using a construction of brick outer leaf, cavity and plastered 125mm solid "Polyblox" " (Boral Edenhall - 1987), which allowing for normal htc's would give an average wall  $\Lambda$  value of  $0.677 \text{ W/m}^2\text{K}$ . The equivalent resistance value of a 125mm composite block (with 25mm of insulation) is specified by the manufacturer as:  $1.044 \text{ (m}^2\text{K/W)}$ .

While in their trade literature, the nominal thickness of a "Polyblox" block is given as 125mm - the insulation layer thickness being 25mm - (Boral Edenhall - 1987), the architectural drawings/Bills of Quantities for this job specify a 130mm block having an insulation layer of 30mm thickness. The company produces special blocks on request and this appears to have been the case. This is substantiated by on-site observations which gave a 30mm thickness of the insulation layer.

According to their Technical Data/Sheet 7 the equivalent resistances of insulating blocks have been calculated using a computer programme to take into account the effect of differing conductivity values of the block background (Boral Edenhall - 1987). Despite their statement that "copies of these calculations are available on request", repeated written and oral requests for access to the calculations were declined. Consequently, the method is not known and a manufacturers value is not available for a 130mm composite block.

The U value was also calculated according to the CIBSE Guide which assumes continuous insulation layer. The best estimate of a wall U value is  $0.60 \text{ W/m}^2\text{K}$  when using a construction of brick outer leaf, cavity and plastered 125mm "Polyblox", which allowing for normal htc's would give an average wall  $\Lambda$  value of  $0.674 \text{ W/m}^2\text{K}$ . The equivalent resistance of the composite block is  $1.048 \text{ (m}^2\text{K/W)}$  [which results by adding the resistance of the dense block (0.088) to the resistance of the 25mm insulation layer

(0.96)]. This compares very favourably with the manufacturers specified value of 1.044 ( $\text{m}^2\text{K/W}$ ), and the CIBSE and the manufacturers values can be considered as being the same.

Applying the CIBSE 1D model to the 130mm block results in a wall  $\Lambda$  value of 0.60  $\text{W/m}^2\text{K}$ . An equivalent resistance value of 1.236  $\text{m}^2\text{K/W}$  was used ( $1.044 + 5\text{mm}/0.026$  - where 5mm is the additional amount of insulation).

**CIBSE area weighted model:**

The area weighted model was also used in order to take into account the effect of the mortar joints. There is no explicit recommended practice on whether the mortar bed finishes on block level or it is flush with the insulation layer either by the British Standards or by the manufacturers literature. However, the best evidence available may be found in Plates 6.1.1 and 6.1.2 which indicate that in the illustrations in the manufacturers data sheets the mortar bed is flush with the insulation layer.

The best estimate of the wall  $\Lambda$  value for a construction of brick outer leaf, cavity and plastered 130mm "Polyblox" is 0.725  $\text{W/m}^2\text{K}$  for a 10mm mortar joint and a block of standard dimensions 440 \* 215 \* 100mm, based on an equivalent resistance for the composite block of 1.236  $\text{m}^2\text{K/W}$ . The proportions for the block and mortar area were taken as 93.43% and 6.56% respectively.

**Finite element model:**

In order to achieve a better approximation, an additional set of calculations was carried out i.e. a 3D finite element model was applied. Two estimates are presented for the  $\Lambda$  value of the "Polyblox" wall, a block average value of 0.97 and a block centre value of 0.94. The block average value considers the heat flow through the total surface of the block including the mortar joints. The data used are given in Table 6.1.8.

The wall surface resistances ( $\text{m}^2\text{K/W}$ ) were taken as follows:

Internal	Cavity	External
0.123	0.09	0.03

When the recess was bridged, the htc was a combination of the convection and radiation components and the normal surface resistance was taken.

<b>Ident: Wall Type A</b>		
<b>Material</b>	<b>Thickness (mm)</b>	<b>Resistance (m<sup>2</sup>K/W)</b>
Brick	100	0.143
Cavity	65	
Insulation	30	1.150
Block	100	0.088
Plaster	13	0.110
Mortar joint	130	0.163
<b>Table 6.1.8:</b> <i>"Polyblox" wall construction details used for thermal modelling</i>		

Two conditions were examined, the recesses bridged by mortar and unbridged.

**bridged recess:**

If the mortar bed does not stop at the block level (Boral Edenhall - 1987) and penetrates the insulation layer, as usually happens in practice (Plates 6.1.1 to 6.1.6), the mortar which is of higher conductivity than the insulation material, is bridging the insulation layer, consequently the resistance of the wall is reduced.

**unbridged recess:**

For an unbridged recess the level of wall performance is effectively determined by the behaviour of the air in the recess. If it can be assumed that the radiation and convection components are negligible in the recesses then it is reasonable to consider that the insulation forms a complete homogeneous layer. This is because the conductivity of dry air is 0.025 W/mK at 10 °C and is equivalent to the conductivity of the insulation (0.028 W/mK).

When the mortar bed stops at block level, the conductivity of the mortar joint has therefore little or no influence on the overall wall resistance since the insulation layer and the still air in the recess forms the largest proportion of the resistance. In this case the FE value should agree with the manufacturers and CIBSE 1D transmittance value of 0.60 W/m<sup>2</sup>K.



However, the presence of a convection current within the recess may result in the  $\Lambda$  value becoming higher than this theoretically minimum value. From experimental data, convection is negligible in an airspace for Grashoff (Gr) numbers less than about 2000 (Fishenden and Saunders - 1950, Anderson 1981-I). The Gr number will perform for free convection much the same function that the Re number does for forced convection.

The Gr number is defined as:

$$Gr = \frac{x^3 g \beta \Delta T \rho^2}{\mu^2}$$

Therefore for a temperature difference ( $\Delta T$ ) of 2K,  $g = 9.81 \text{ m/s}^2$ ,  $\beta = 1$ ,  $\mu = 14.19 \times 10^{-6} \text{ m}^2/\text{s}$  at 10 °C, and  $x = 235\text{mm}$  for a vertical recess or  $x = 10\text{mm}$  for a horizontal recess (values were taken from Tables of properties of air)

Gr number for a vertical recess =  $4468 \times 10^3$

Gr number for a horizontal recess = 344

The convection in the horizontal recess is therefore minimal or non existent. The same cannot be said for the vertical recess with a Gr number of  $4468 \times 10^3$  which indicates that convection may very well be taking place.

Given the above results, on-site observations and the manufacturers data it is reasonable to conclude that whether the recess is bridged with mortar or there are convection currents across the vertical recess, the inner leaf of the wall tends to behave in the same manner. Therefore only the values associated with the bridging of the insulation layer are considered to be representative of the wall performance and are examined in the next section.



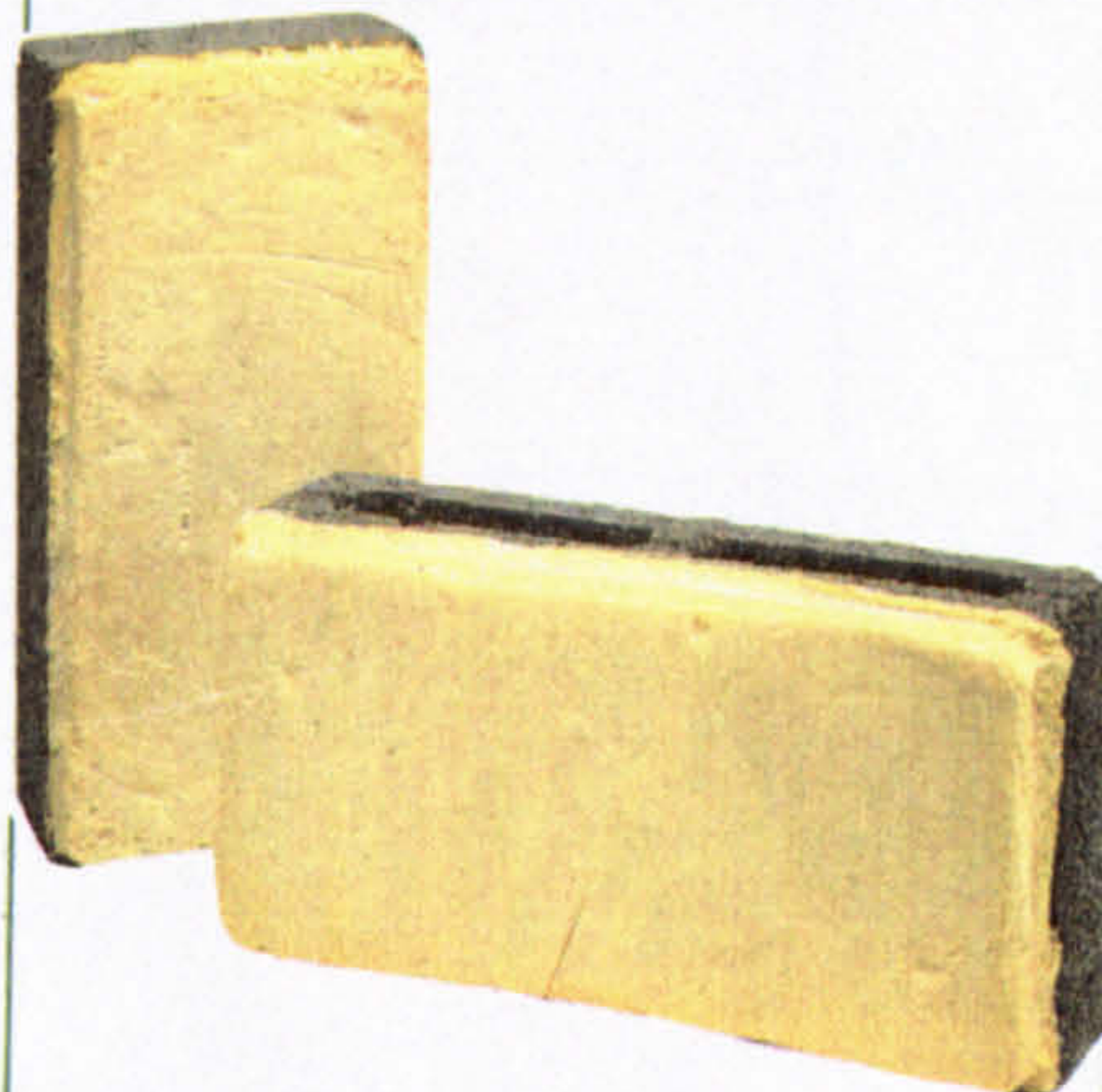


**Plate 6.1.1:**

**Plates 6.1.1 and 6.1.2:**

*Building practice for a "Polyblox" wall as illustrated in the manufacturers trade literature (bridged recesses at the insulation level, i.e. mortar joints finishing flush with the insulation layer)*

*(After Boral Edenhall - 1987)*



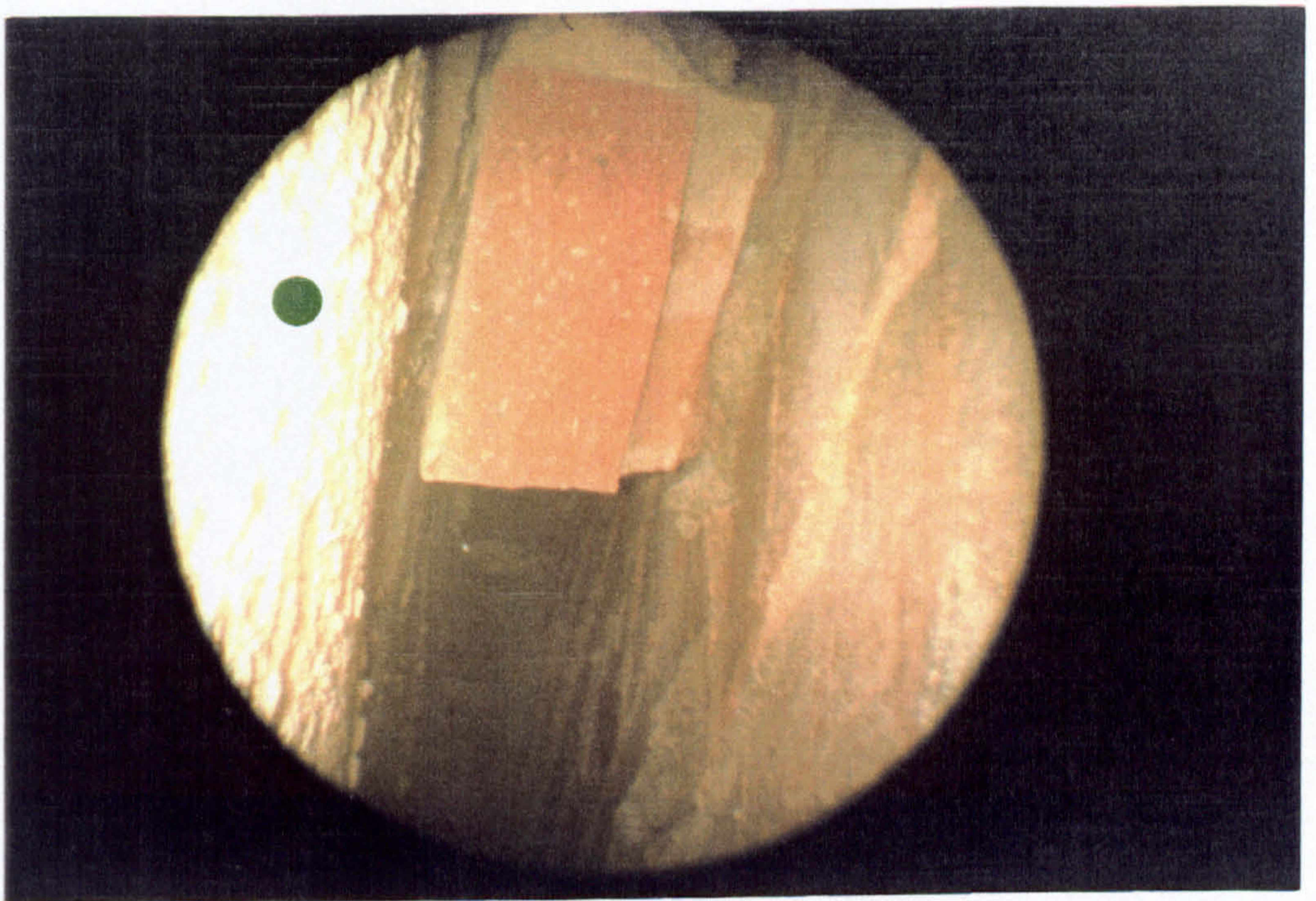
**Plate 6.1.2:**



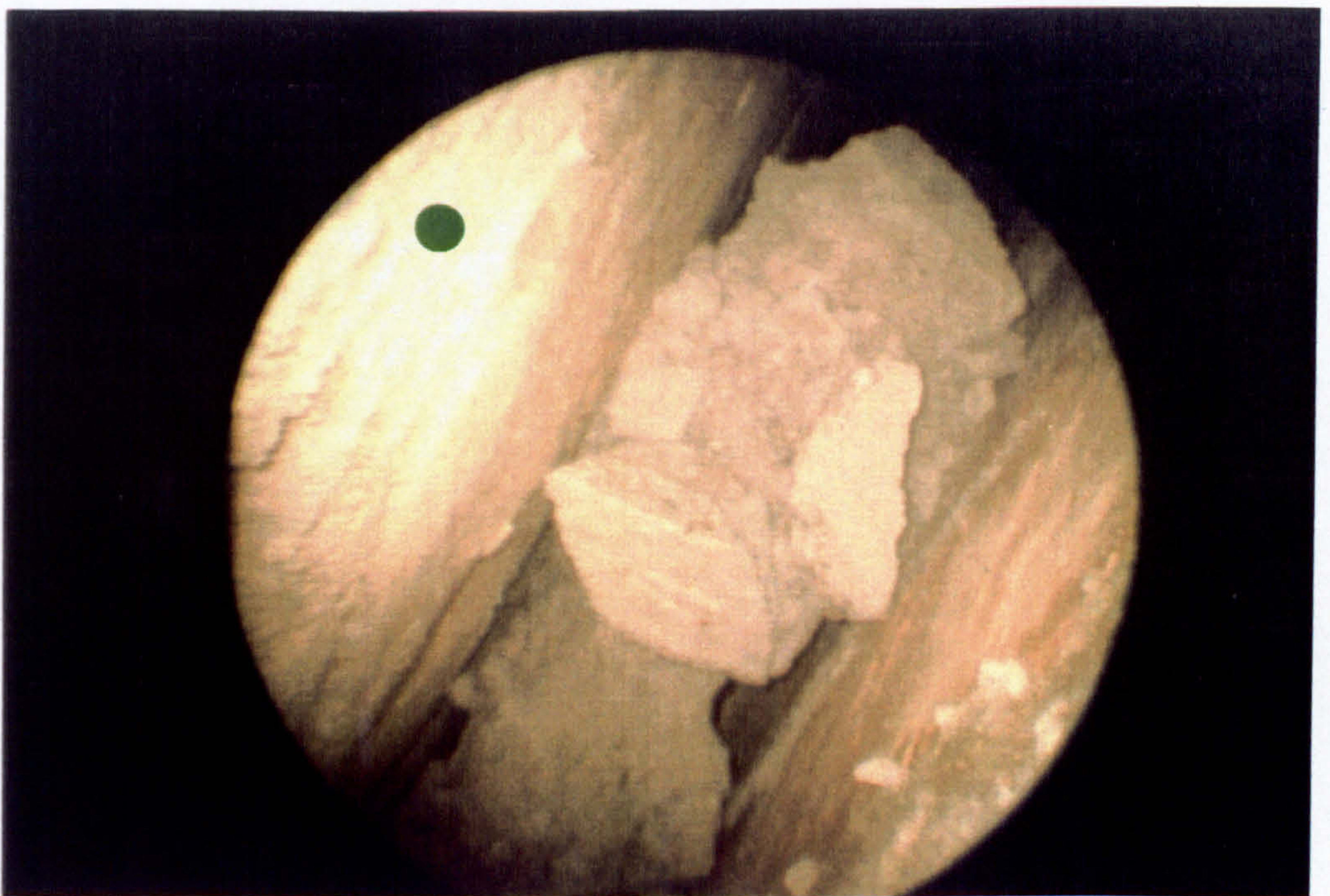
# **CURRENT BUILDING PRACTICE FOR COMPOSITE BLOCKS**

**[It should be emphasised that the cavity airspace shown in Plates 6.1.3 to 6.1.6 is part of the wall construction where the T value measurements were made at N. Tyneside Hospital (Residence quarters). The block is of the "Polyblox" type (the insulation made from polyurethane). It can be seen in all Plates that the mortar joints finish flush with the insulation layer (the green dot indicates the insulated side of the cavity). In addition, four examples of poor work practice are given, all bridging the cavity airspace forming potential cold bridges and including whole or half sized bricks (Plates 6.1.3 and 6.1.5), building debris (Plate 6.1.4) and mortar droppings on a wall tie (Plate 6.1.6). Photographs were taken on the same wall.]**



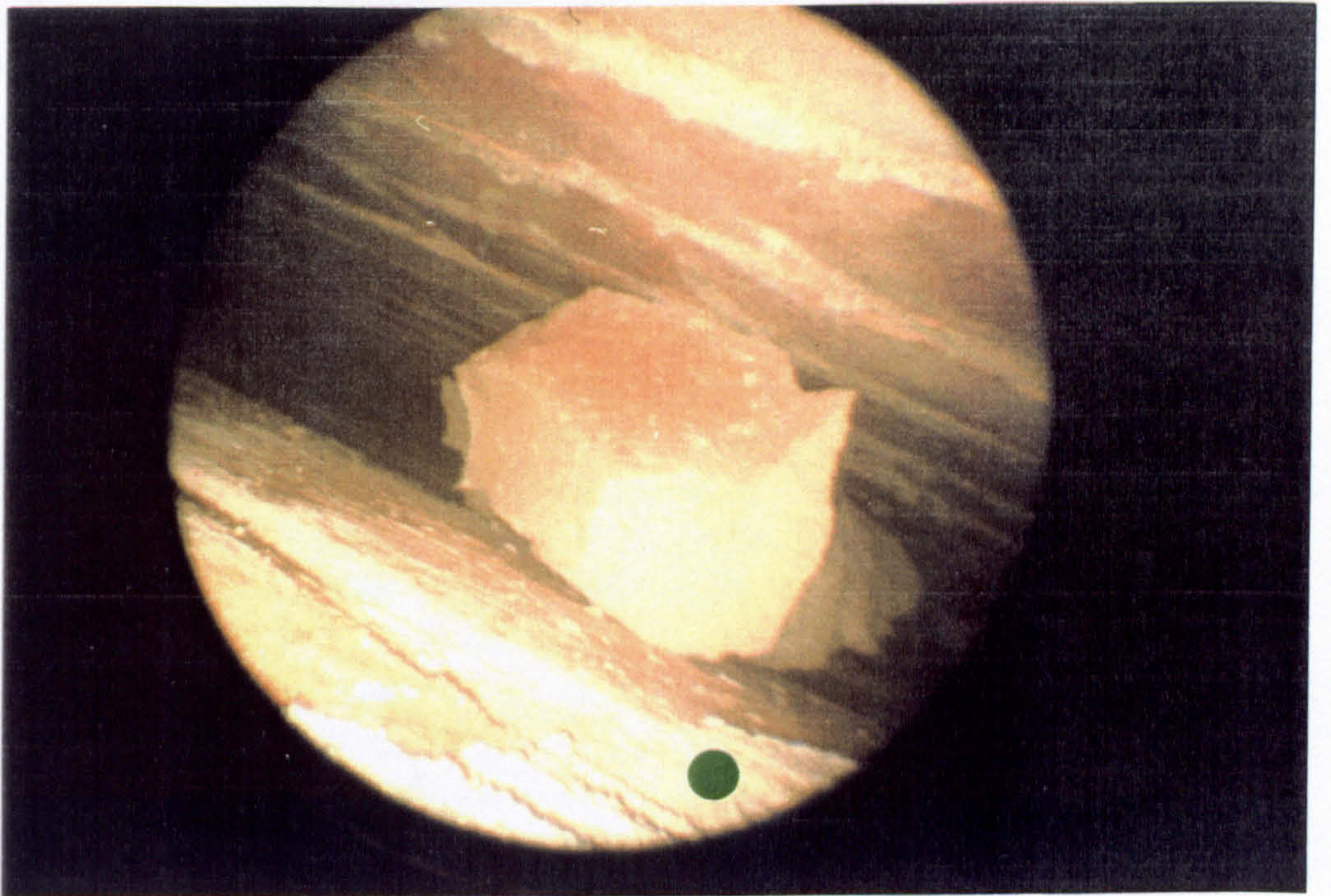


*Plate 6.1.3:*

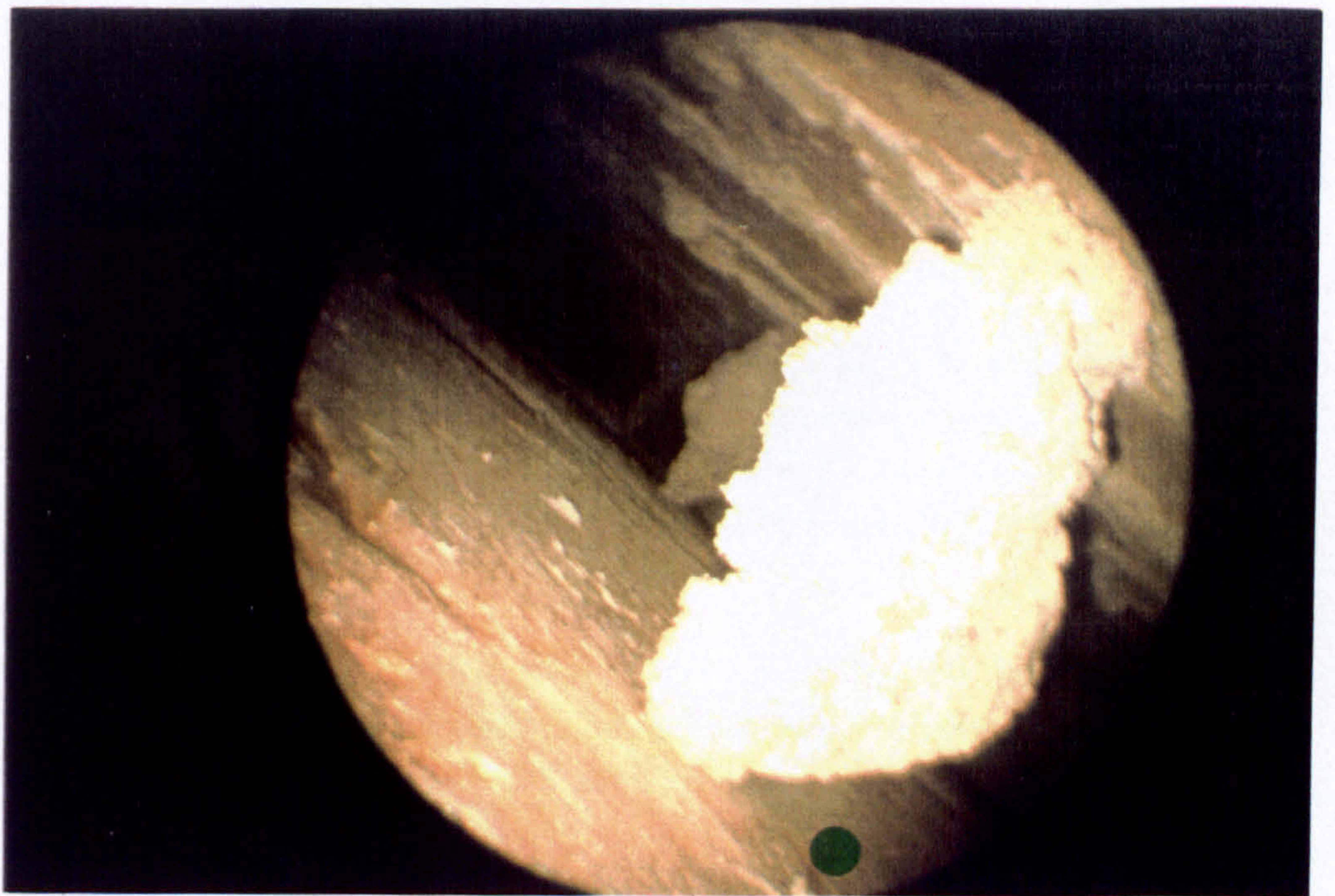


*Plate 6.1.4:*





*Plate 6.1.5:*



*Plate 6.1.6:*



6.1.6 Comparison between the measured and theoretical transmittance values

The values obtained for the thermal transmittance of the wall are shown in Table 6.1.9.

	FE Model ling	CIBSE Guide 1D	Area Weighted	Manufa cturers value*	Measured value
Block average	0.97	X	0.725		0.87
Block centre	0.94	0.60	X	0.60	
Block average/ Block centre	1.03		1.21		
* Adjusted for 130mm composite block (30mm of insulation).					
<b>Table 6.1.9:</b> <i>FE, CIBSE and measured transmittance (W/m<sup>2</sup>K) values for a brick/cavity/"Polyblox"/plaster wall - Wall type A</i>					

It is clear from Table 6.1.9 that the manufacturers and the CIBSE 1D values are the same. The manufacturers values are therefore optimistic in that they assume a homogeneous wall construction with no cold bridging due to the mortar joints.

The FE block average and block centre values are in close agreement with each other, being 0.97 and 0.94 respectively. The explanation for this is that the high conductivity of the dense solid concrete block and mortar joints equalises the temperature profile within the depth of the wall resulting in a nearly uniform surface temperature distribution giving rise to a uniform heat flow into the wall.

As expected the FE block centre value is considerably higher when compared to the manufacturers and CIBSE 1D values of 0.60 because the 1D representation does not take into account the influence of the cold bridging by the mortar joints within the recesses between the insulation.



As expected the CIBSE area weighted value of 0.725 lie between the lower limit of the CIBSE 1D and manufacturers value of 0.6 and the higher limit of the FE block average value of 0.97. The FE block average takes into account the 3D effect, whereas the area weighted is only an approximate 2D representation. In other words, the area weighted model takes into account the cold bridging of the mortar joints at the recess level but it does not account for the 3 dimensional flux distortion that the mortar joints produce. The mortar joints perform like a heat sink through the insulation depth and would therefore result in the area weighted model underestimating the increase in transmittance. For this construction type the expectation is that the FE value provides a much more complete representation of the wall performance.

Because a nearly uniform surface temperature is expected it is reasonable to assume that the measured value should be independent of position and be representative of the average performance of the wall construction. The measured value of 0.87 lies between the area weighted and the FE values and it tends to be more in line with the value resulting from the FE modelling.

Given the experimental errors and the uncertainty in calculating the theoretical performance due to possible differences in material properties and dimensions between the "as built" and theoretical walls, there is a reasonable agreement between the FE and the measured values. The manufacturers value may be considered to have a typical uncertainty limit of  $\pm 4.2\%$  (chapter 4), whereas the mean of the measured values has a limit of  $\pm 2.15\%$ .

Every effort was made for the sensors to be placed at a thermally uniform location on the wall surface and reasonable agreement between wall positions was expected. However, there was still a considerable variation between wall positions, especially for Site 1 where a variation of 25% was obtained (excluding sensor 65/M2), a variation of 20% for Site 2 and 27.5% for Site 3. The overall variation across the three Sites was 39.5%, from a minimum value of 0.7009 (Site 1) to a maximum value of 1.0441 (Site 3). This is equivalent to a standard error of 7.7% for the determination of the transmittance at a single position (see also page 6.15).

In summarising the evidence with respect to the variability of heat flow, the following three points are clear:

- (1) The FE modelling suggests that heat flow into the wall is relatively uniform, i.e., it is independent of the position on the wall surface.
- (2) The measured values suggest that there is a 39.5% variation in heat flow between the wall positions across the three Sites.
- (3) Infrared analysis suggests no gross thermal abnormalities. More detailed analysis however revealed that the wall surface temperature is non-uniform.

The variations between the measured values for the 9 wall positions may be due to the following causes, a number of them relating directly to workmanship applied during construction:

(1) Damaged or missing insulation. Photographic evidence has proven this to be a common defect on building sites where composite blocks are used (Plates 6.1.7 to 6.1.10).

(2) It is possible to get local differences in the thermal performance of the wall because of a number of inconsistencies which may have an important role to play, such as, differences in the way in which the blocks are bedded, the thickness/continuity of the mortar joint, differences in the way in which the mortar joint finishes i.e. finishing flush with the insulation layer at the recess level or protruding in the cavity airspace (Plates 6.1.1 to 6.1.4 and Plate 6.1.10). While there is no manufacturers specific reference on the treatment of the recesses (the vertical and horizontal openings formed by adjacent blocks at the level of the insulation layer), inspection of building sites in the Newcastle area (supported by photographic evidence) revealed that the mortar joints frequently extend beyond the concrete layer, finishing flush/recessed with the insulation in the cavity or/and protruding into the cavity airspace. Similar illustrative evidence is also provided by the manufacturers trade literature (Plates 6.1.1 and 6.1.2). This "bridging" of the insulation layer with a high conductivity mortar reduces considerably the insulation properties of the construction.

(3) Protrusions into the cavity airspace (Plates 6.1.3 to 6.1.6). The Plates indicate that whole or half sized bricks or mortar droppings are inside the cavity forming a potential cold bridge. At the point of contact the insulation material may be damaged providing a path across the cavity. This type of defect is not clear on the infrared monitor but it may very well contributing to a higher heat flow path through the block. In other words the infrared camera with a minimum temperature resolution of 0.1 °C may scan a uniform or nearly uniform temperature field at the internal surface of the wall but high heat flows may go through certain positions. The high density/conductivity blockwork effectively redistributes any temperature fluctuations before they are scanned by the infrared camera.

A point which is common to all Sites and which mainly has to do with the conditions of measurement is that the HFSs placed at the upper part of the wall surface always record higher than the HFSs at the lower part of the wall i.e. 19% for Site 1, 4% for Site 2 and 9% for Site 3. These values were obtained by taking the mean value resulting from the upper HFSs and the mean value resulting from the lower HFSs and calculating the percentage difference between them. The reasons for these differences may be as follows:



(1) The wall surface temperature is lower towards the ceiling which means that the heat flow through the wall is not 1D, i.e., the heat flow will be directed to the colder upper part of the wall which is not normal to the plane of the wall.

(2) In this construction the space above the ceiling is classified as ventilated space and there is no legal requirement to achieve a U value of  $0.6 \text{ W/m}^2\text{K}$ . Therefore "Polyblox" construction may or may not be used above the ceiling line. If this is the case it will certainly contribute to the upper HFS registering a higher heat flow than the lower HFSs. A number of reasons are given below:

Cold bridging may be formed due to the temperature of the void above the ceiling line being considerably lower (because of ventilation, absence of plaster and insulation, air-entrainment through the structure above the ceiling line). The above will therefore influence to a considerable extent the temperature of the wall surface just below the ceiling.

(3) A temperature gradient on the wall surface is clearly illustrated in Plates 6.1.11 and 6.1.13. An apparent uniformity (uniform boundary conditions) is indicated over the area where the HFS was placed with a  $1^\circ\text{C}$  temperature differential. However a more detailed analysis in Plates 6.1.12 and 6.1.14 indicates that the wall surface temperature is non-uniform and exhibits a stratified temperature gradient with a  $0.2/0.3^\circ\text{C}$  temperature difference in each layer. This temperature stratification is not due to some discontinuity in the wall but due to the environmental conditions within the room and may contribute into setting-up complex 3D heat flow patterns and dissipation of energy within the blockwork itself which in turn means that the heat flow into the wall is not uniform. Therefore, because of lateral heat flows the HFSs may record values which are higher or lower than the average performance of the block.

(4) The HFS may be placed at different distances from or on a cold bridge (Plates 6.1.15 and 6.1.16). A very realistic cause for the sensor placed at this particular position to record higher values than the other positions. Because of the geometry the measurement is taking place in a highly unstable field and it is strongly dependent on the exact position of the measurement.

The measured results indicate that the transmittance values are up to approximately 45% greater than the design value and a single position on the wall may not be indicative of the average performance of the wall.



As far as the variability in the performance of the wall is concerned it is not possible to distinguish whether the resulting overall 39.5% variation in the measured values across the 3 Sites is due to the wall or due to the combined effect of a number of causes that they were outlined above, such as, complex 3D heat flow effects taking place within the blockwork layer due to temperature stratification, cold bridges, variable htc's and different standards of workmanship.

In other words, the "Polyblox" wall may behave in a very uniform manner (the intrinsic behaviour of the wall is uniform) and the variability in performance being a function of workmanship, the design of the construction and the environmental conditions.

Despite these variabilities there is some evidence to suggest that this wall behaves on average, close to its theoretical performance. From this study the best estimate for the measured average performance of the wall is 0.87 which lies between the area weighted value of 0.725 and the FE block average value of 0.97. The differences between the above values may seem large but given the uncertainty in the measurement and the uncertainty involved in calculating the theoretical values, the wall is more or less performing in line with its theoretical capabilities. The U value of  $0.6 \text{ W/m}^2\text{K}$  which was adopted for the original design specifications fails to take into account the average performance of the wall. Therefore, if the value resulting from the CIBSE 1D model which is traditionally employed as a design tool, is compared with the measured value, it seriously underestimates the average performance of the wall.

However, if the average performance of the wall is to be assessed correctly on a theoretical basis, a more sophisticated model than the CIBSE 1D basic model must be used. If 2D or 3D FE modelling facilities are not available then the CIBSE area weighted model is recommended for this type of wall construction.

**CURRENT BUILDING PRACTICE**  
**FOR**  
**COMPOSITE BLOCKS**

**[It should be emphasised that the blocks shown in Plates 6.1.7 to 6.1.10 are for indicative purposes only and they are of the "Polybond" type (the insulation made from polystyrene) and not of the "Polyblox" type (the insulation made from polyurethane)].**





*Plate 6.1.7:*

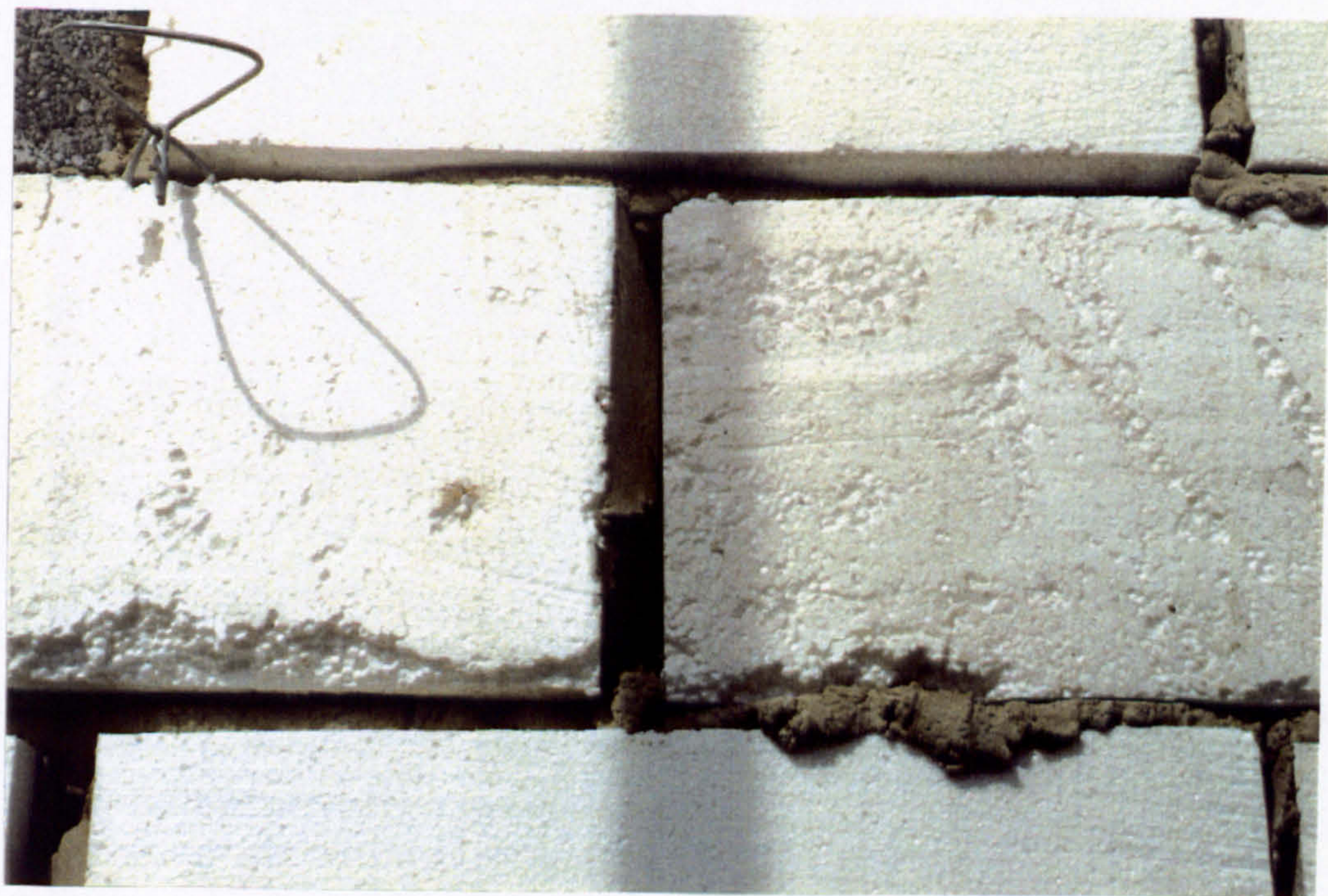


*Plate 6.1.8:*





*Plate 6.1.9:*

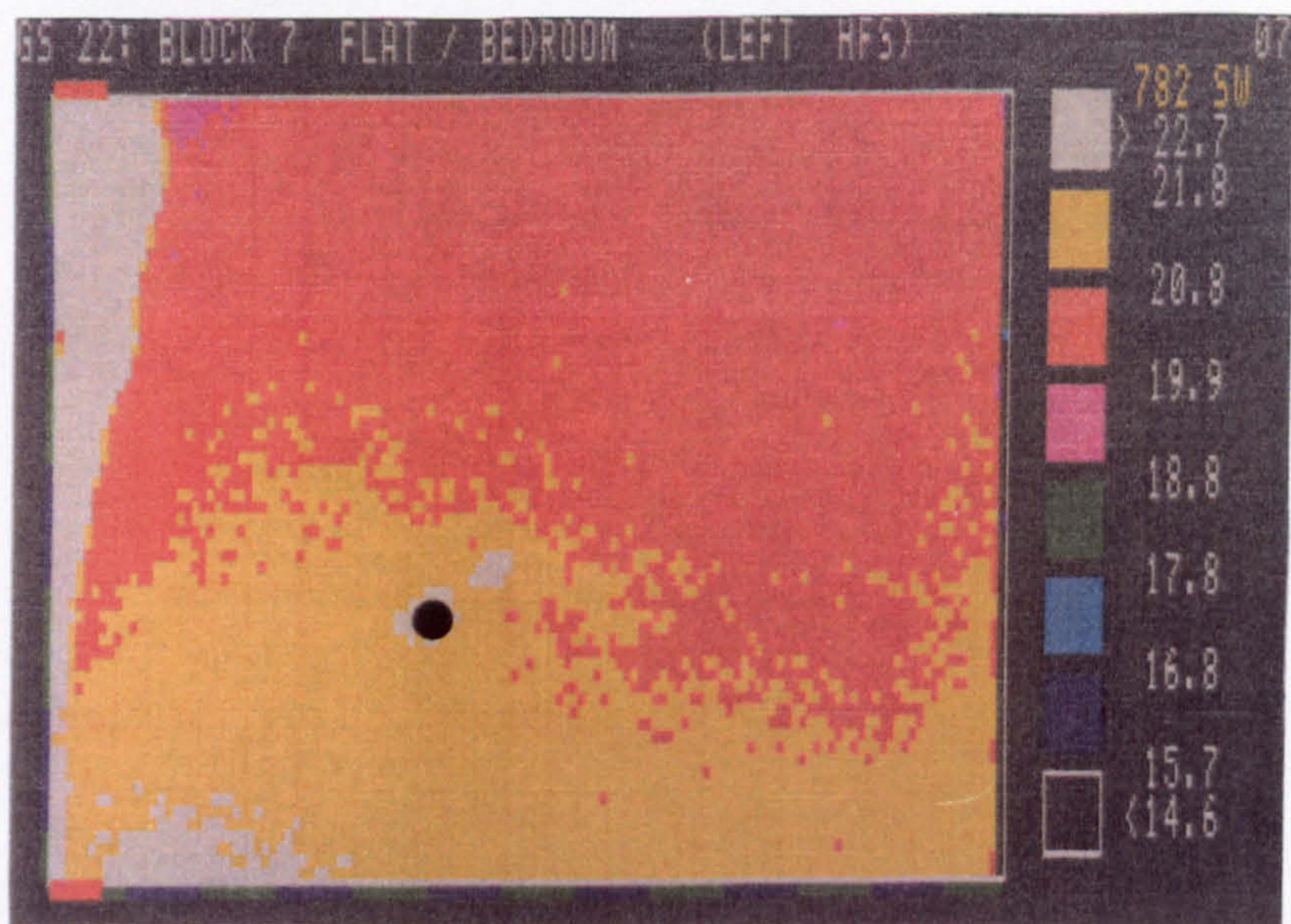


*Plate 6.1.10:*



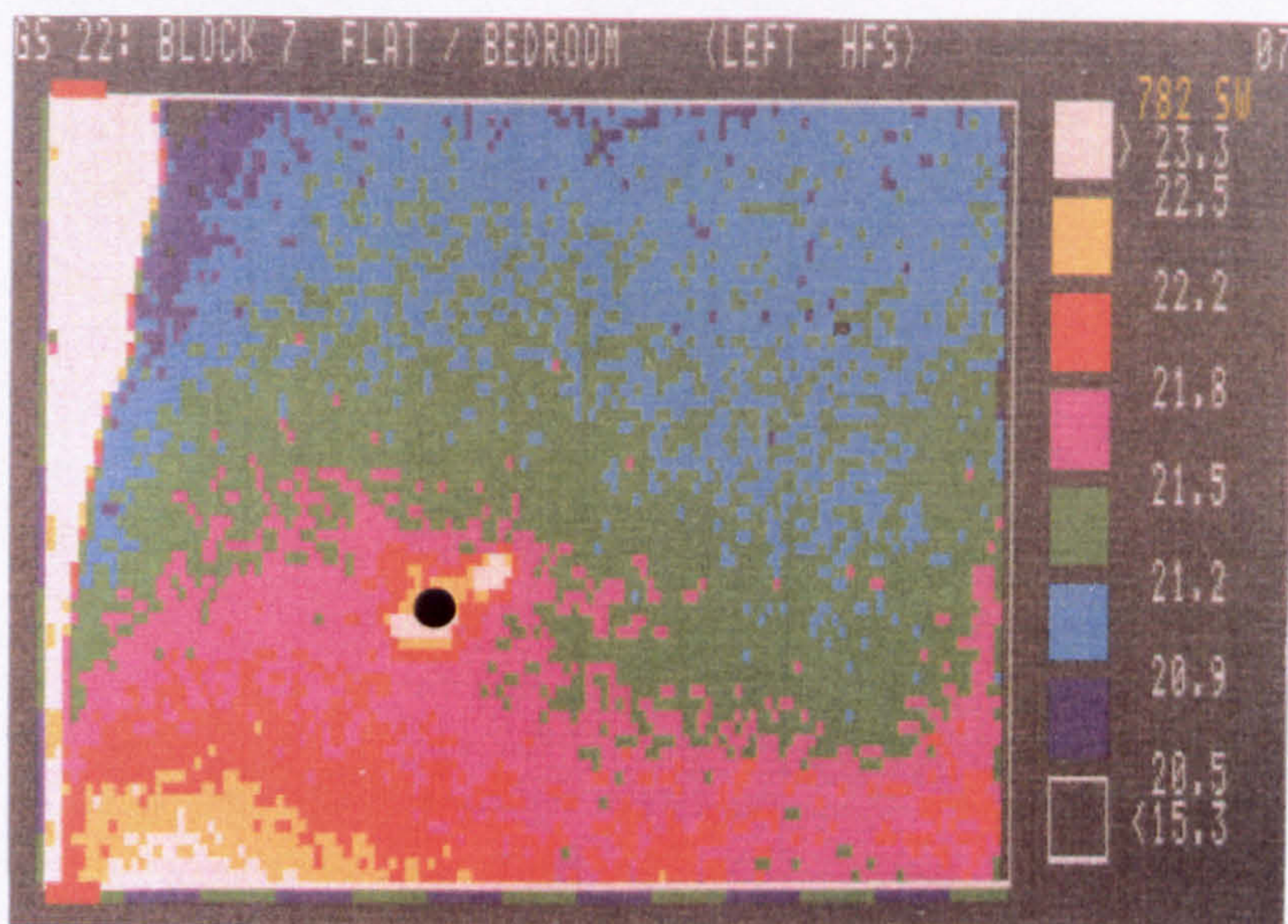
## **THERMOGRAMS**





**Plate 6.1.11:**

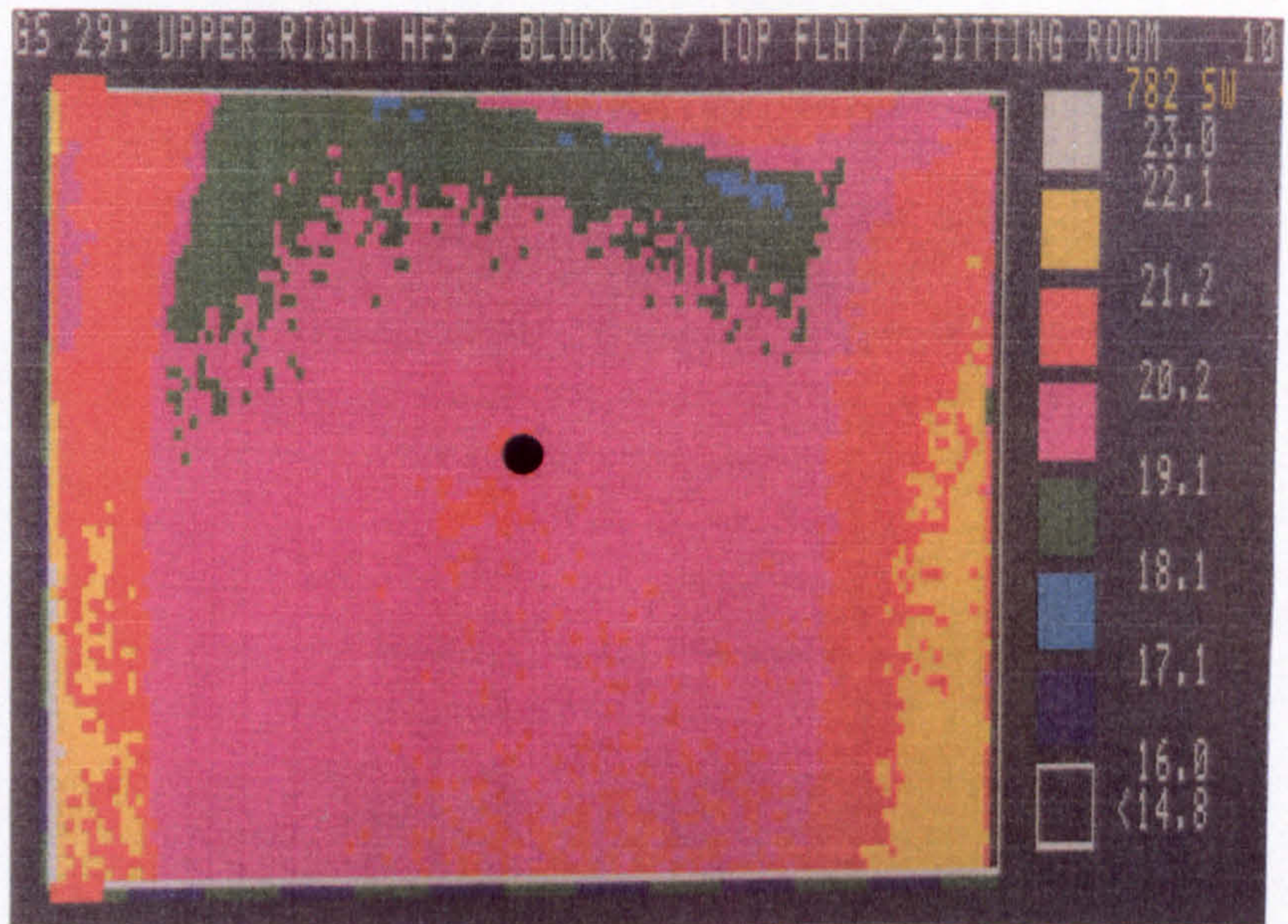
The thermogram indicates nearly uniform conditions across the wall surface. However, this is not the case (see Plate 6.1.12 below). The black dot indicates the exact position of the HFS on the surrounding wall surface. (Site 1). A temperature differential of 1 °C across the surface can also be seen.



**Plate 6.1.12:**

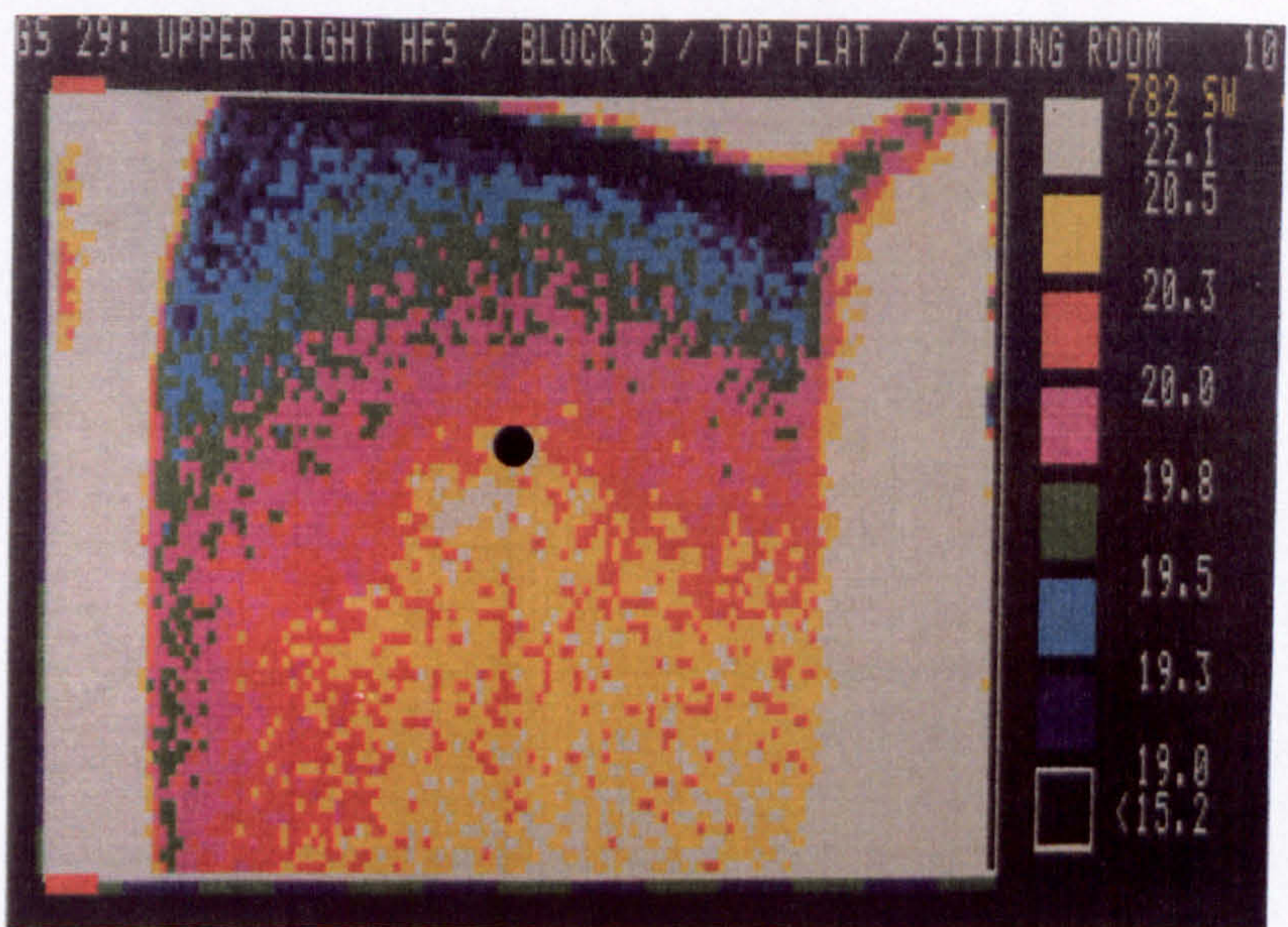
Detailed analysis of the above thermogram (Plate 6.1.11) indicates the stratified nature of the temperature distribution across the wall surface. The black dot indicates the exact position of the HFS on the surrounding wall surface. A temperature differential of 0.3 °C across the surface can also be seen.





**Plate 6.1.13:**

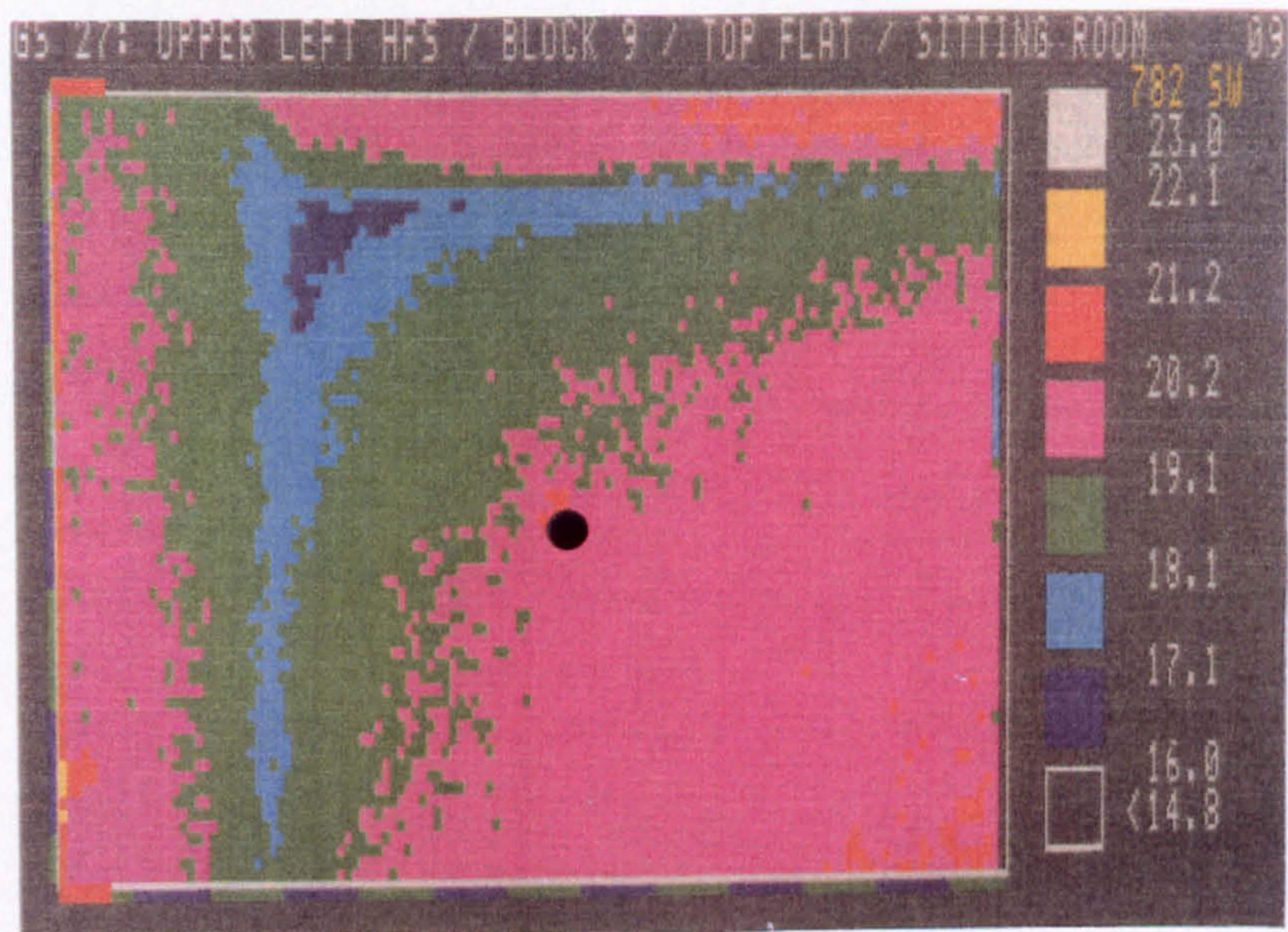
The thermogram indicates nearly uniform conditions across the wall surface. However, this is not the case (see Plate 6.1.14 below). The black dot indicates the exact position of the HFS on the surrounding wall surface. (Site 2). A temperature differential of 1 °C across the surface can also be seen.



**Plate 6.1.14:**

Detailed analysis of the above thermogram (Plate 6.1.13) indicates the stratified nature of the temperature distribution across the wall surface. The black dot indicates the exact position of the HFS on the surrounding wall surface. A temperature differential of 0.2/0.3 °C across the surface can also be seen. It is obvious that the surface temperature becomes progressively lower towards the upper part of the wall.

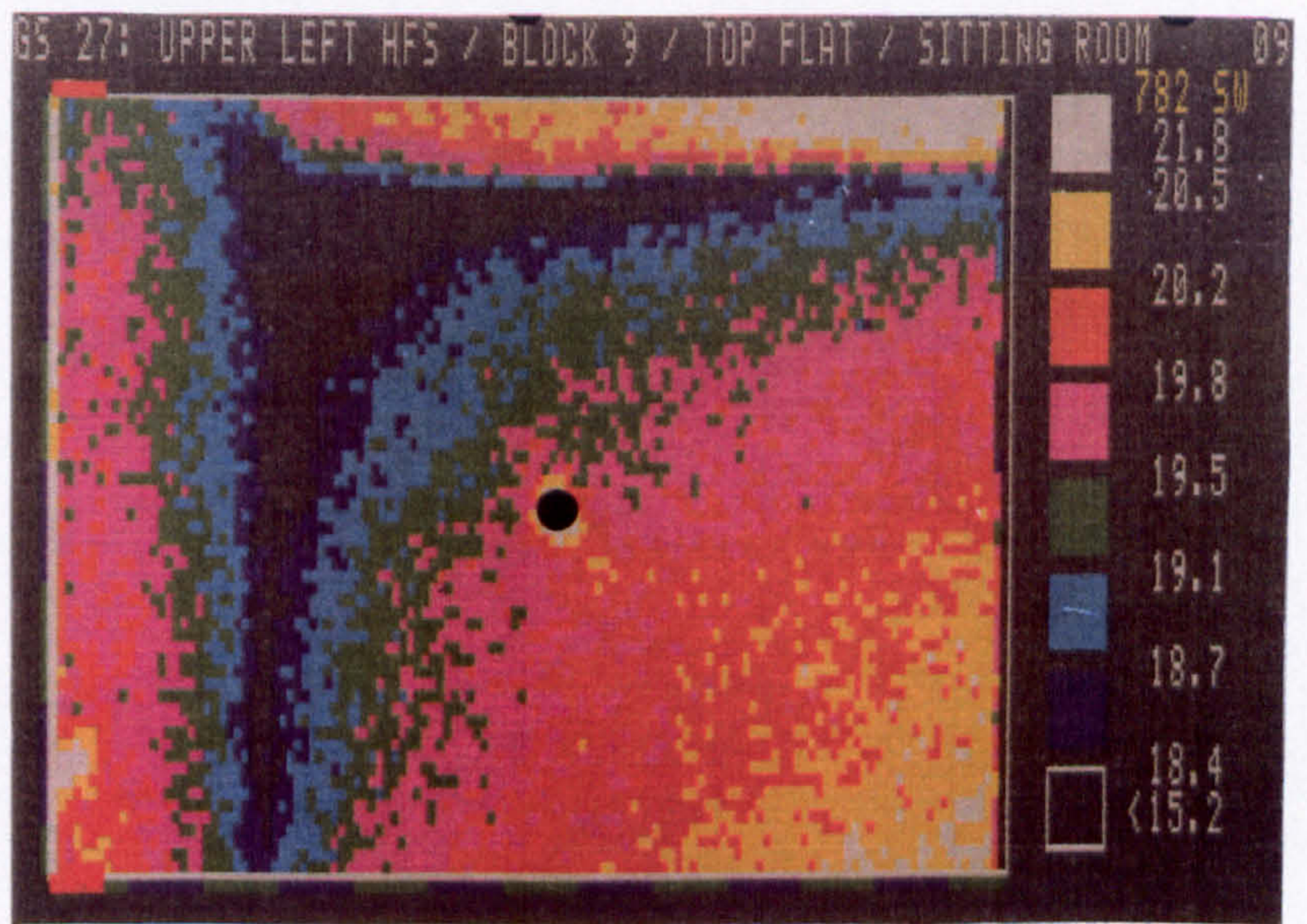




**Plate 6.1.15:**

The thermogram indicates that the HFS was placed near a cold bridge (the only available location). The black dot indicates the exact position of the HFS on the surrounding wall surface. (Site 2).

A temperature differential of 1 °C across the surface can also be seen.



**Plate 6.1.16:**

Detailed analysis of the above thermogram (Plate 6.1.15) indicates the stratified nature of the temperature distribution across the wall surface. The black dot indicates the exact position of the HFS on the surrounding wall surface.

A temperature differential of 0.3/0.4 °C across the surface can also be seen.



**WALL DETAILS**

**PHYSICAL DESCRIPTION  
OF  
THE WALL**

ID: WALL TYPE A	<b>PROPERTIES OF WALL CONSTRUCTION</b>
SITE: NORTH TYNESIDE HOSPITAL (RESIDENCE QUARTERS)	
SITE No.: 8	SERIES OF MEASUREMENT:
DATE: WINTER 88	
CONSTRUCTION YEAR: 1987	
FILENAME:	

<b>INNER LEAF: "POLYBLOX" DENSE CONCRETE STANDARD BLOCKWORK</b>																												
<table style="width: 100%; border: none;"> <tr><td>PLASTER .....</td><td style="text-align: right;">YES</td></tr> <tr><td>DENSITY (Kg/m<sup>3</sup>) .....</td><td style="text-align: right;"></td></tr> <tr><td>PLASTER DENSITY .....</td><td style="text-align: right;">770</td></tr> <tr><td>DENSITY (mean) .....</td><td style="text-align: right;">1480</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) .....</td><td style="text-align: right;"></td></tr> <tr><td>PLASTER SPECIFIC HEAT CAPACITY .....</td><td style="text-align: right;">1000</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) .....</td><td style="text-align: right;">916</td></tr> <tr><td>THICKNESS (m) .....</td><td style="text-align: right;">0.130</td></tr> <tr><td>PLASTER THICKNESS .....</td><td style="text-align: right;">0.013</td></tr> <tr><td>THICKNESS (total) .....</td><td style="text-align: right;">0.143</td></tr> <tr><td>CONDUCTIVITY (W/mK) .....</td><td style="text-align: right;"></td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) .....</td><td style="text-align: right;">1.236</td></tr> <tr><td>PLASTER RESISTANCE .....</td><td style="text-align: right;">0.110</td></tr> <tr><td>RESISTANCE (total) .....</td><td style="text-align: right;">1.346</td></tr> </table>	PLASTER .....	YES	DENSITY (Kg/m <sup>3</sup> ) .....		PLASTER DENSITY .....	770	DENSITY (mean) .....	1480	SPECIFIC HEAT CAPACITY (J/KgK) .....		PLASTER SPECIFIC HEAT CAPACITY .....	1000	SPECIFIC HEAT CAPACITY (mean) .....	916	THICKNESS (m) .....	0.130	PLASTER THICKNESS .....	0.013	THICKNESS (total) .....	0.143	CONDUCTIVITY (W/mK) .....		RESISTANCE (m <sup>2</sup> K/W) .....	1.236	PLASTER RESISTANCE .....	0.110	RESISTANCE (total) .....	1.346
PLASTER .....	YES																											
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PLASTER RESISTANCE .....	0.110																											
RESISTANCE (total) .....	1.346																											

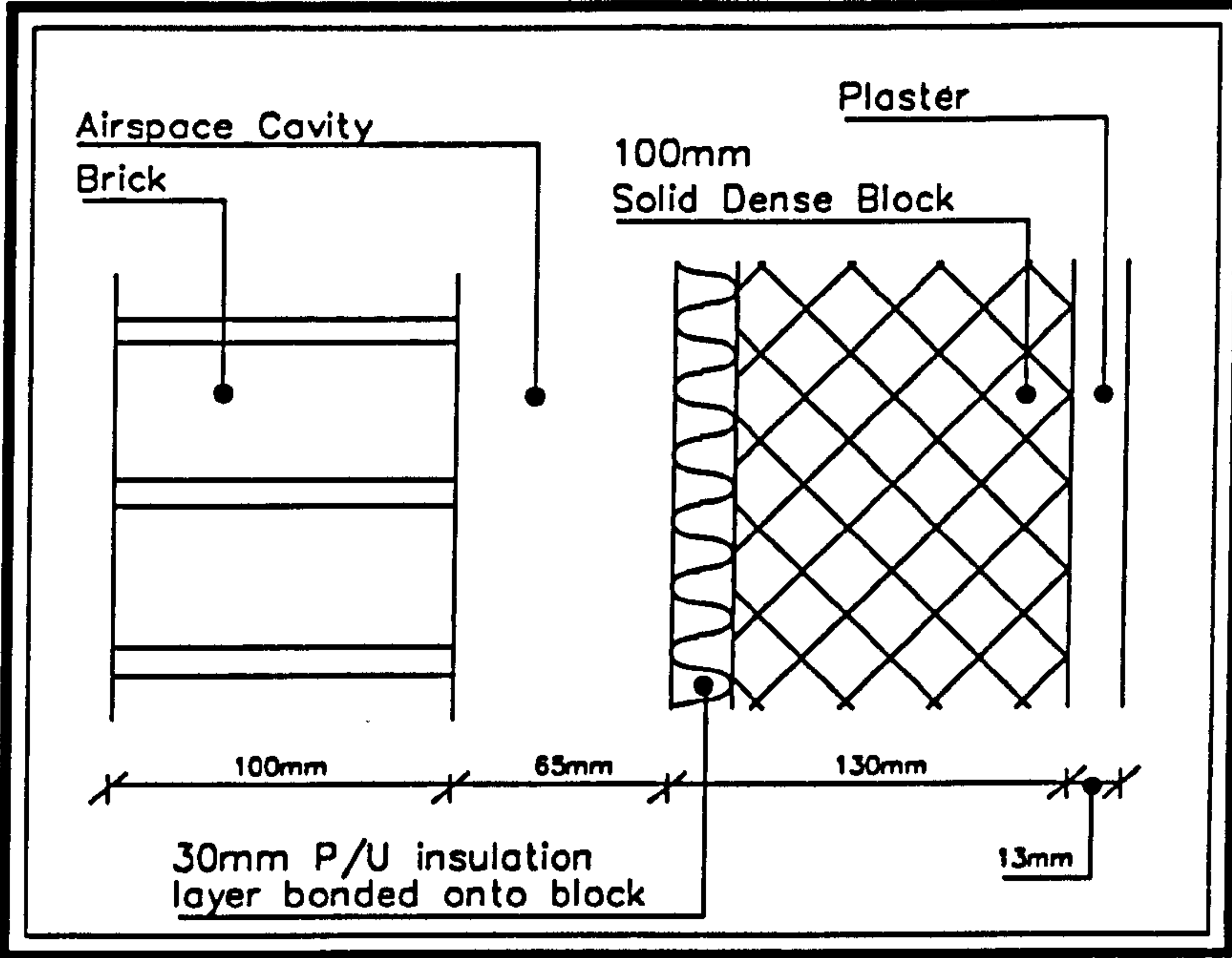
<b>OUTER LEAF: DESFORD OLD ENGLISH MULTI-BUFF WIRE CUT BRICK</b>																												
<table style="width: 100%; border: none;"> <tr><td>RENDER ? .....</td><td style="text-align: right;">NO</td></tr> <tr><td>DENSITY (kg/m<sup>3</sup>) .....</td><td style="text-align: right;">1396</td></tr> <tr><td>RENDER DENSITY .....</td><td style="text-align: right;"></td></tr> <tr><td>DENSITY (mean) .....</td><td style="text-align: right;">1396</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) .....</td><td style="text-align: right;">790</td></tr> <tr><td>RENDER SPECIFIC HEAT CAPACITY .....</td><td style="text-align: right;"></td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) .....</td><td style="text-align: right;">790</td></tr> <tr><td>THICKNESS (m) .....</td><td style="text-align: right;">0.1</td></tr> <tr><td>RENDER THICKNESS .....</td><td style="text-align: right;"></td></tr> <tr><td>THICKNESS (total) .....</td><td style="text-align: right;">0.1</td></tr> <tr><td>CONDUCTIVITY (W/mK) .....</td><td style="text-align: right;">0.7</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) .....</td><td style="text-align: right;">0.143</td></tr> <tr><td>RENDER RESISTANCE .....</td><td style="text-align: right;"></td></tr> <tr><td>RESISTANCE (total) .....</td><td style="text-align: right;">0.143</td></tr> </table>	RENDER ? .....	NO	DENSITY (kg/m <sup>3</sup> ) .....	1396	RENDER DENSITY .....		DENSITY (mean) .....	1396	SPECIFIC HEAT CAPACITY (J/KgK) .....	790	RENDER SPECIFIC HEAT CAPACITY .....		SPECIFIC HEAT CAPACITY (mean) .....	790	THICKNESS (m) .....	0.1	RENDER THICKNESS .....		THICKNESS (total) .....	0.1	CONDUCTIVITY (W/mK) .....	0.7	RESISTANCE (m <sup>2</sup> K/W) .....	0.143	RENDER RESISTANCE .....		RESISTANCE (total) .....	0.143
RENDER ? .....	NO																											
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RESISTANCE (m <sup>2</sup> K/W) .....	0.143																											
RENDER RESISTANCE .....																												
RESISTANCE (total) .....	0.143																											

CAVITY ? 65mm	VENTILATED CAVITY ? NO	INSULATION ?
CAVITY RESISTANCE: 0.180		INSULATION RESISTANCE:
HFS No.		HFS CALIBRATION FACTOR:

**Table 6.1.1:**  
*Properties of wall construction - Wall type A*





**Fig. 6.1.1:**  
*Cross section through the wall construction - Wall type A*

**SITE 1**

**LOCATION OF HFSs**

**AND**

**DATA ANALYSIS**



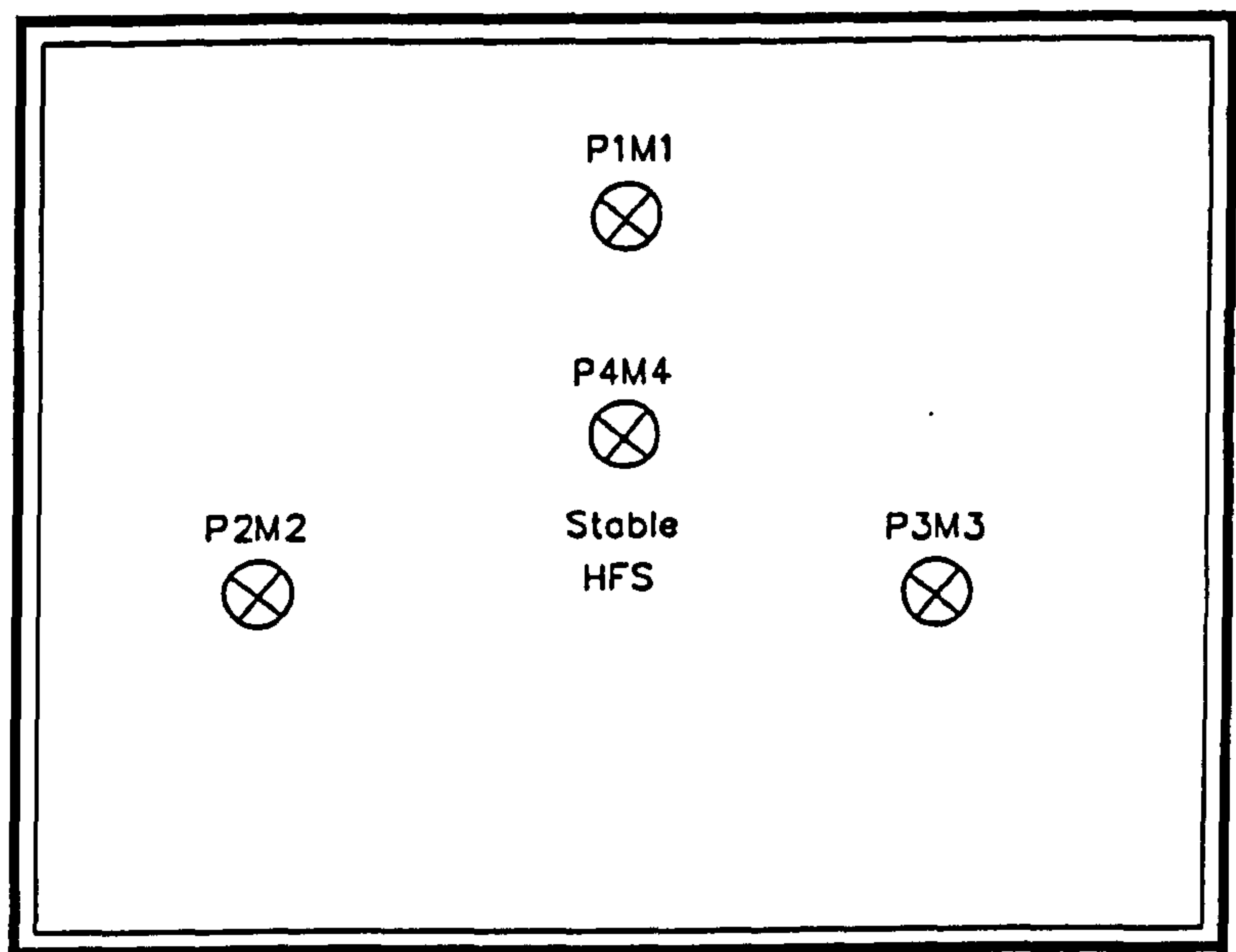


Fig. 6.1.2:  
Position of HFSs on the wall surface - Site 1 - Wall type A

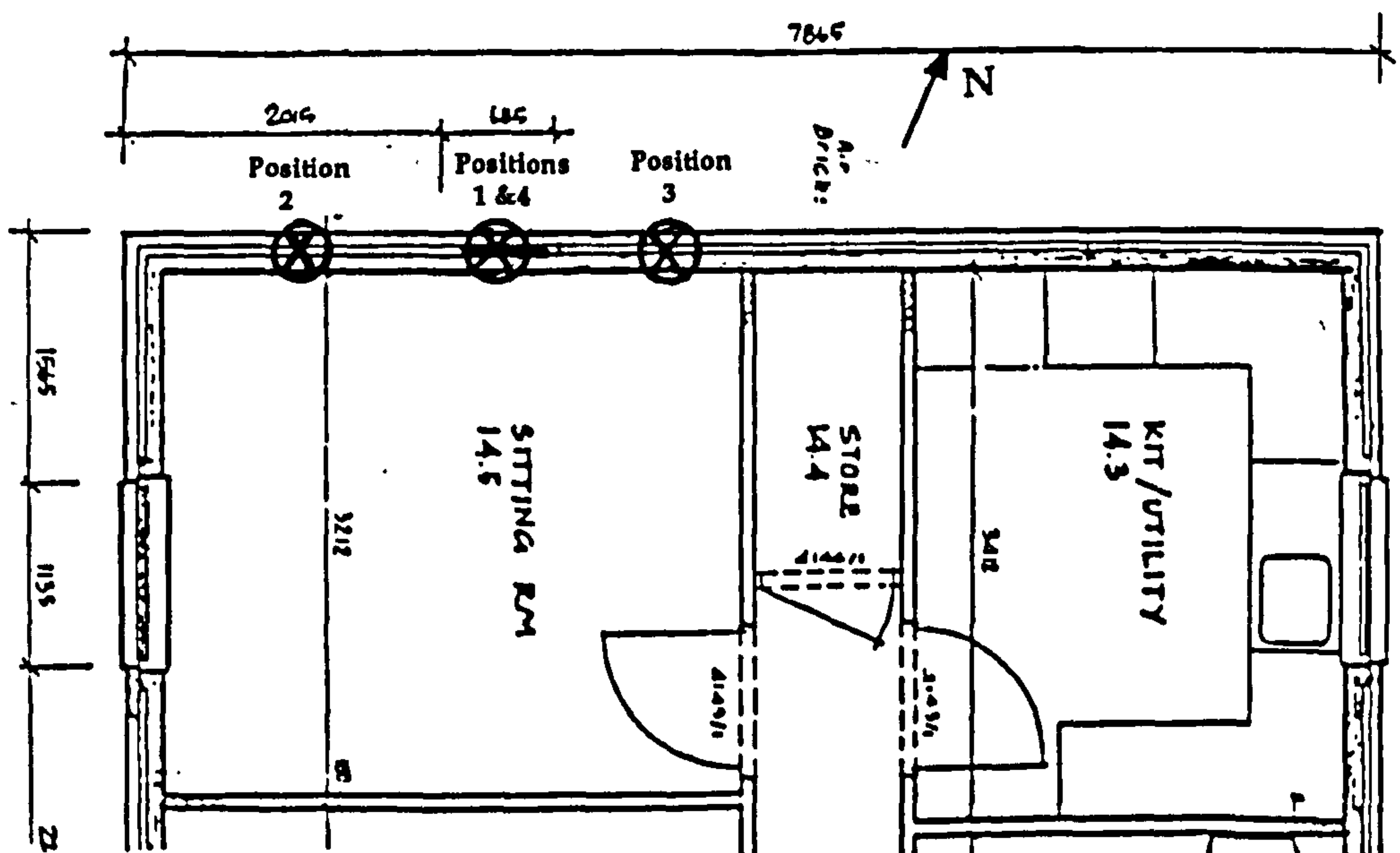
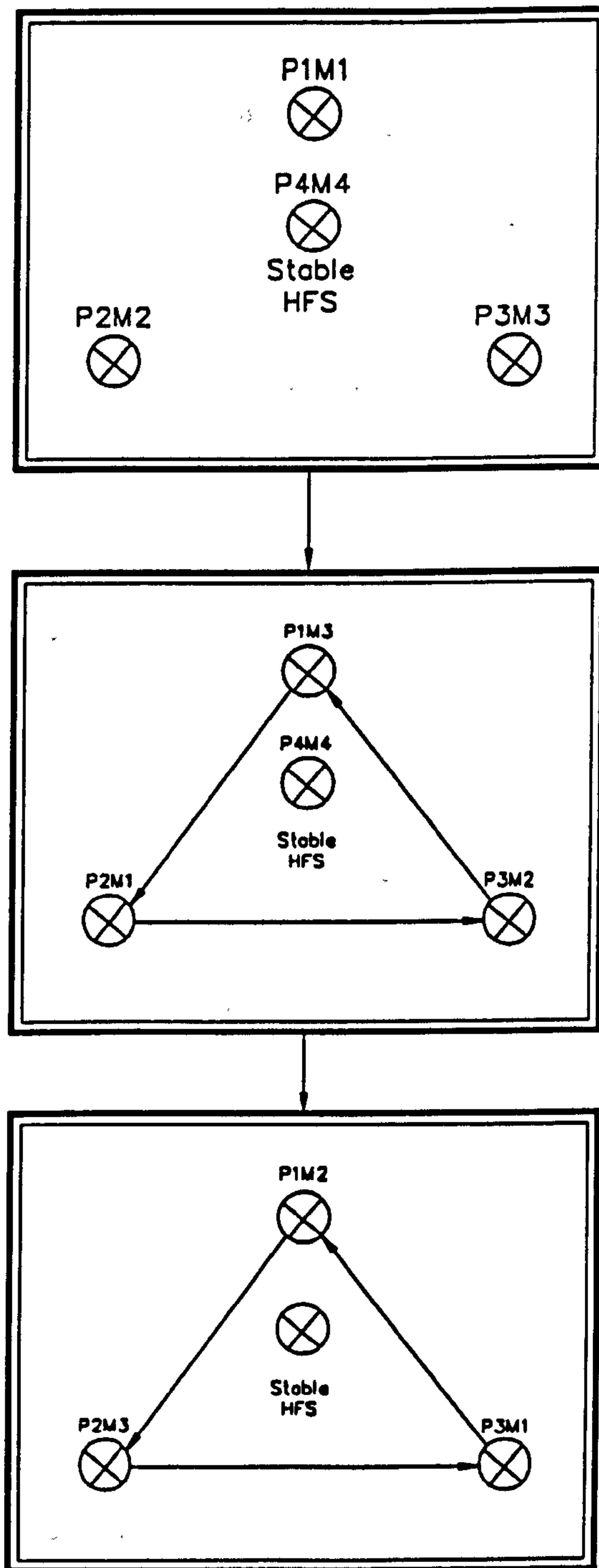


Fig. 6.1.3:  
Location of HFSs on the wall surface - Plan view - Site 1 - Wall type A



**Fig. 6.1.4:**

*HFSs rotation pattern - Site 1 - Wall type A*



Position	Sensor No:	Averaging Method $\Lambda'$ Value			Anderson Method $\Lambda$ Value			Averaging Corrected Value $\frac{\text{Value}}{\text{Anderson Corrected Value}}$
		Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	
1	64	0.8423	0.8393	0.8813	0.8579	0.8548	0.8975	0.9819
2	65	0.9325	0.9683	1.0167	0.9475	0.9839	1.0331	0.9841
3	66	0.6750	0.6589	0.6918	0.6933	0.6767	0.7105	0.9737
4	68	0.8488	0.8437	0.8859	0.8645	0.8593	0.9023	0.9818
1	66	0.8794	0.8584	0.9013	0.8796	0.8586	0.9015	0.9998
2	64	0.7700	0.7672	0.8056	0.7691	0.7667	0.8050	1.0007
3	65	0.7695	0.7990	0.8390	0.7695	0.7990	0.8390	1.0000
4	68	0.8392	0.8342	0.8759	0.8393	0.8343	0.8760	0.9999
1	65	0.9458	0.9821	1.0312	0.9526	0.9892	1.0387	0.9928
2	66	0.7624	0.7440	0.7812	0.7692	0.7508	0.7883	0.9910
3	64	0.6659	0.6635	0.6967	0.6699	0.6675	0.7009	0.9940
4	68	0.8299	0.8249	0.8661	0.8373	0.8323	0.8739	0.9911
MEAN VALUE ➡								0.9904

Table 6.1.2:  
Results - Site 1 - Wall type A


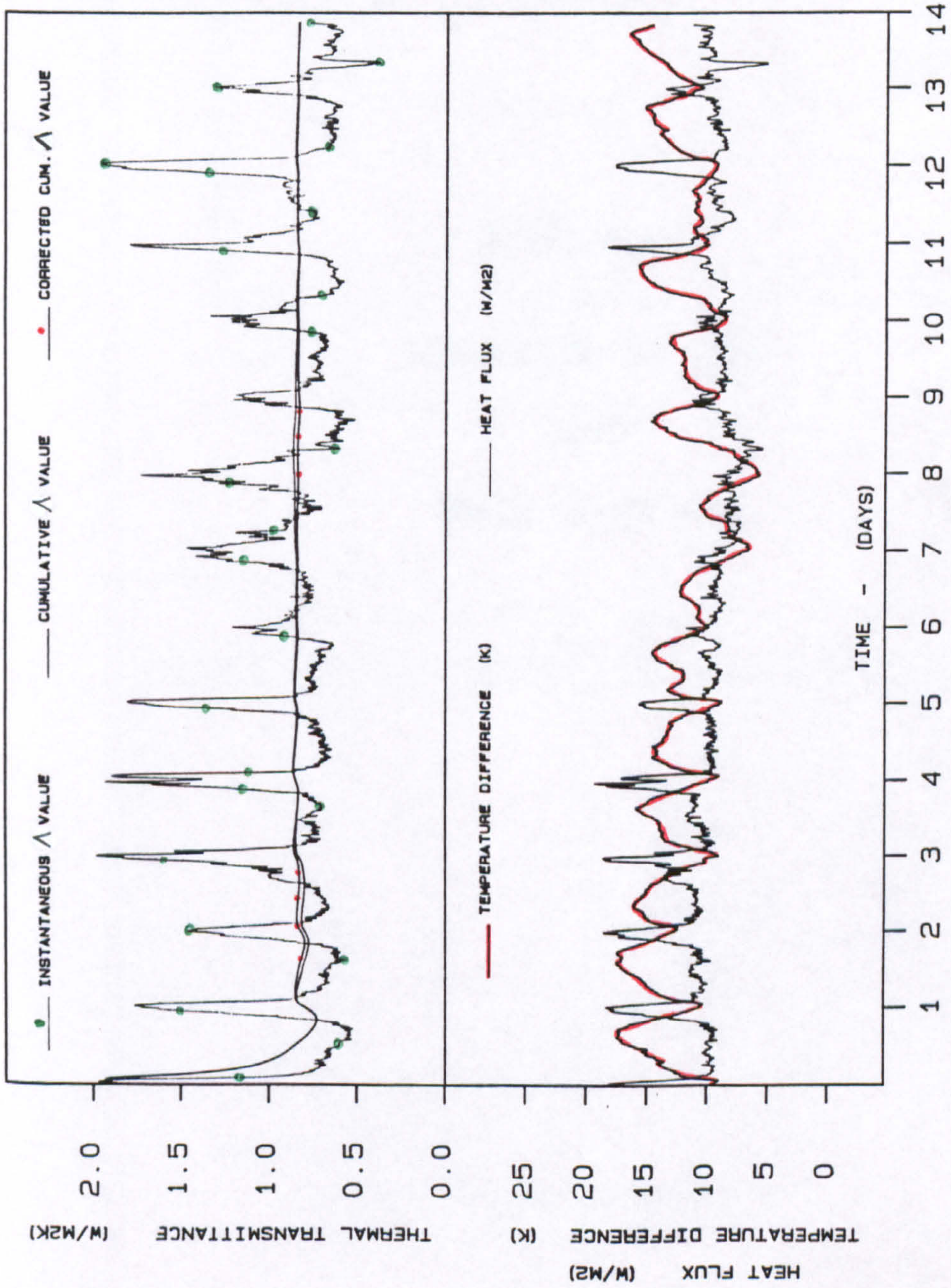
SENSOR SERIAL NO:	POSITION MAT	P1	P2	P3	P4	P5	P6
64	M1	0.8975	0.8050	0.7009			
65	M2	(1.0387)	(1.0331)	(0.8390)			
66	M3	0.9015	0.7883	0.7105			
68	M4				0.9023 0.8760 0.8739		
	M5						
	M6						
MEAN		0.8995	0.7967	0.7057	0.8841		

Table 6.1.3:  
Results - Matrix format - Site 1 - Wall type A





START DATE: 02/11/88
END DATE: 16/11/88
DURATION: 14 DAYS
LOCATION:
N. TYNESIDE HOSPITAL - (BLOCK 7)
RECORDING INSTRUMENT / No.
C / 68
WALL CONSTRUCTION:
OUTER LEAF: DESFORD BRICK
INSULATION: YES (SEE "POLYBLOCK")
INNER LEAF: "POLYBLOCK" BLOCK
FILE NAME: N2TB7C4.001
COMMENTS:
N. TYNESIDE HOSPITAL - BLOCK 7 4 HFS'S WERE USED TO RECORD THE HEAT FLOW ON THE SAME WALL, AT DIFFERENT POSITIONS. 2nd SERIES.
BUILDING SCIENCE SECTION SCHOOL OF ARCHITECTURE NEWCASTLE UNIVERSITY

Fig. 6.1.5:  
Indicative sample of temperature difference, heat flux, instantaneous  $\Lambda$  value,  
cumulative (Averaging)  $\Lambda$  value, corrected (Anderson)  $\Lambda$  value for Site 1 -  
Wall type A



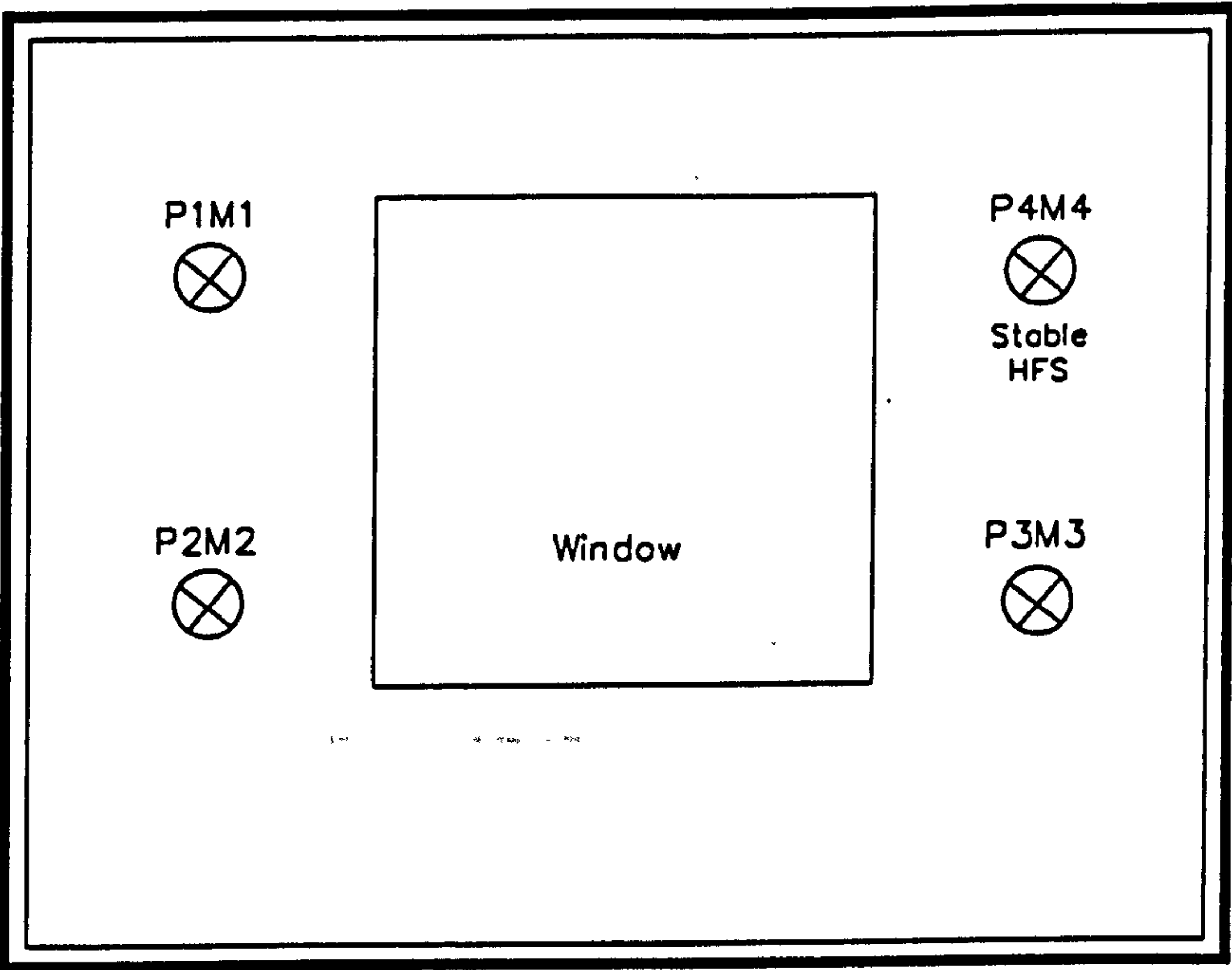
**SITES 2 & 3**

**LOCATION OF HFSs**

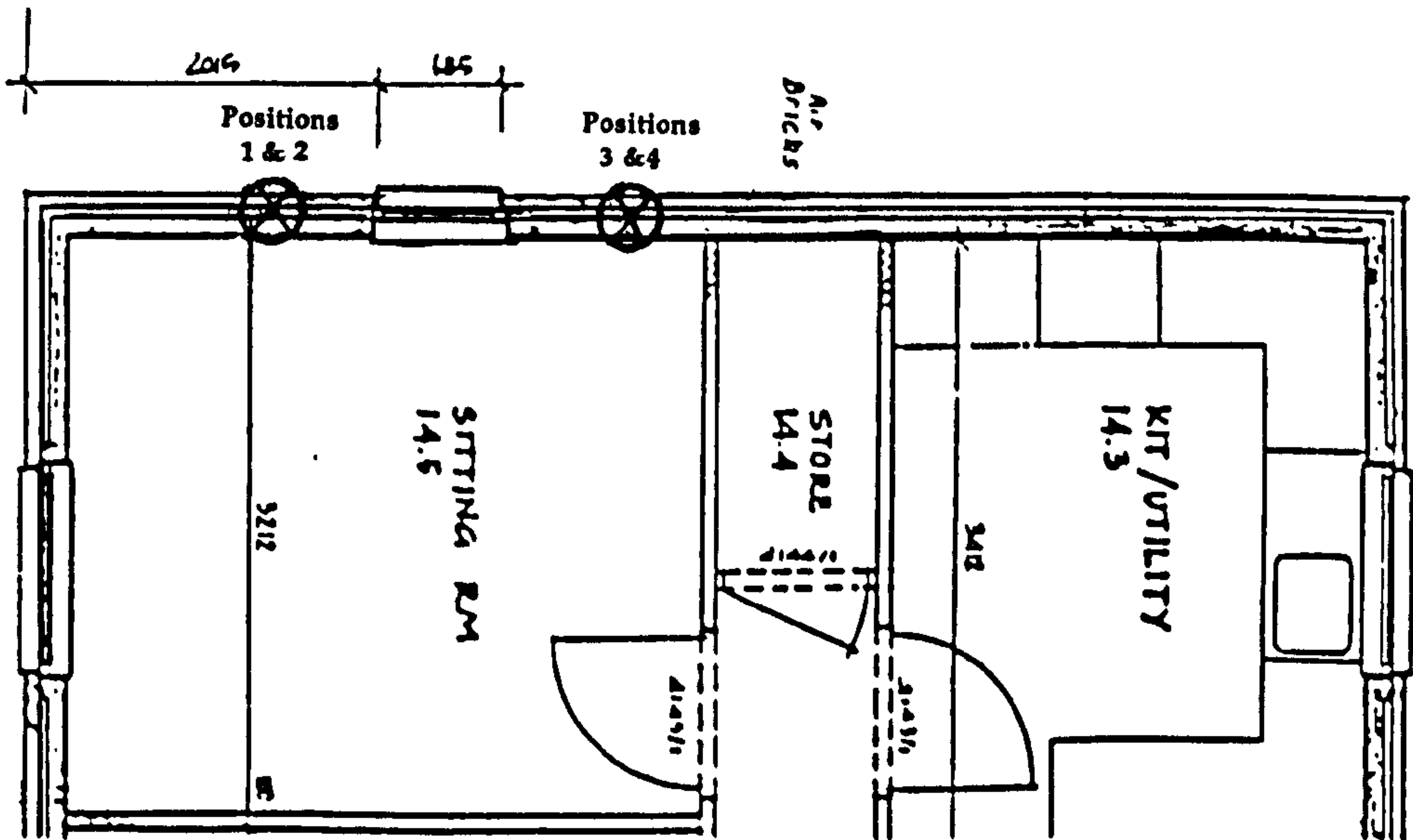
**AND**

**DATA ANALYSIS**





**Fig. 6.1.6:**  
*Position of HFSs on the wall surface - Sites 2 and 3 - Wall type A*



**Fig. 6.1.7:**  
*Location of HFSs on the wall surface - Plan view  
 - Sites 2 and 3 - Wall type A*

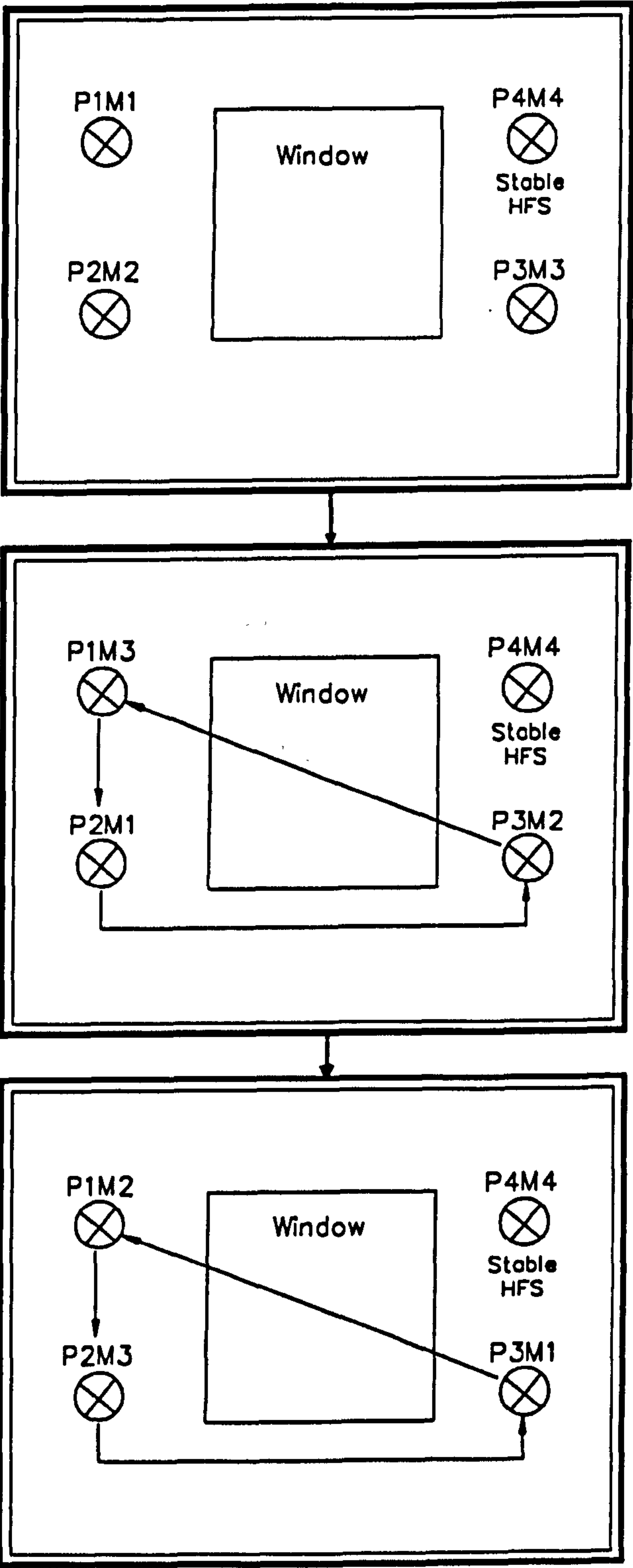


Fig. 6.1.8:  
HFSs rotation pattern - Sites 2 and 3 - Wall type A



## **SITE 2**

## **RESULTS**

Position	Sensor No:	Averaging Method $\Lambda$ Value			Anderson Method $\Lambda$ Value			Averaging Corrected Value
		Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Anderson Corrected Value
1	56	0.8425	0.8571	0.9000	0.8673	0.8823	0.9264	0.9715
2	70	0.8174	0.8098	0.8503	0.8414	0.8336	0.8753	0.9714
3	72	0.7404	0.7300	0.7665	0.7600	0.7494	0.7869	0.9741
4	67	0.8393	0.8275	0.8689	0.8653	0.8532	0.8759	0.9699
1	72	0.8362	0.8242	0.8654	0.8400	0.8280	0.8694	0.9954
2	56	0.8923	0.9077	0.9531	0.8961	0.9116	0.9572	0.9957
3	70	0.8118	0.8043	0.8445	0.8093	0.8018	0.8419	1.0031
4	67	0.8718	0.8596	0.9026	0.8724	0.8602	0.9032	0.9993
1	70	0.8394	0.8316	0.8732	0.8433	0.8355	0.8773	0.9953
2	72	0.8064	0.7949	0.8346	0.8098	0.7982	0.8381	0.9958
3	56	0.8058	0.8197	0.8607	0.8076	0.8216	0.8627	0.9977
4	67	0.8704	0.8582	0.9011	0.8717	0.8595	0.9025	0.9984
MEAN VALUE ➡		0.8311	0.8271	0.8684	0.8404	0.8362	0.8781	0.9890

**Table 6.1.4:**  
*Results - Site 2 - Wall type A*




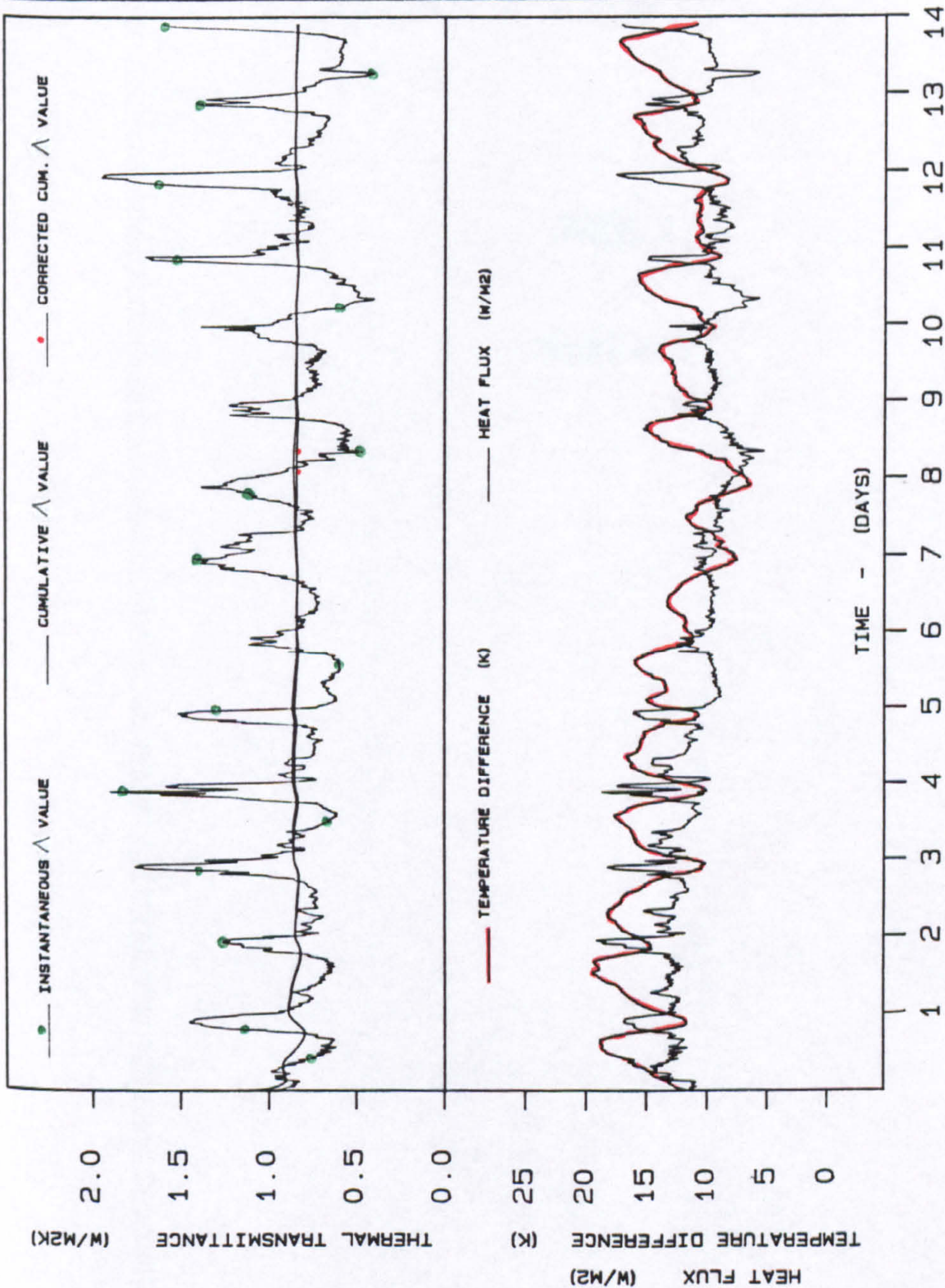
SENSOR SERIAL NO:	POSITION MAT	P1	P2	P3	P4	P5	P6
56	M1	0.9264	0.9572	0.8627			
70	M2	0.8773	0.8753	0.8419			
72	M3	0.8694	0.8381	0.7869			
67	M4				0.8959 0.9032 0.9025		
	M5						
	M6						
MEAN		0.8910	0.8902	0.8305	0.9005		

Table 6.1.5:  
Results - Matrix format - Site 2 - Wall type A





START DATE: 02/11/88
END DATE: 16/11/88
DURATION: 14 DAYS
LOCATION:
N. TYNESIDE HOSPITAL - (BLOCK 9)
RECORDING INSTRUMENT / No.
I / 72
WALL CONSTRUCTION:
OUTER LEAF: DESFORD BRICK
INSULATION: YES (SEE "POLYBLOCK")
INNER LEAF: "POLYBLOCK" BLOCK
FILE NAME: N2TB919.001
COMMENTS:
N. TYNESIDE HOSPITAL / BLOCK 9 4 HFS'S WERE USED TO RECORD HEAT FLOW ON THE SAME WALL, AT DIFFERENT POSITIONS. 2nd SERIES.
BUILDING SCIENCE SECTION SCHOOL OF ARCHITECTURE NEWCASTLE UNIVERSITY

Fig. 6.1.9:  
Indicative sample of temperature difference, heat flux, instantaneous  $\Lambda$  value,  
cumulative (Averaging)  $\Lambda$  value, corrected (Anderson)  $\Lambda$  value for Site 2 -  
Wall type A



## **SITE 3**

## **RESULTS**

Position	Sensor No:	Averaging Method $\Lambda$ Value			Anderson Method $\Lambda$ Value			Averaging Corrected Value
		Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Anderson Corrected Value
1	71	0.9707	0.9888	1.0382	0.9762	0.9944	1.0441	0.9943
2	70	0.7967	0.7893	0.8288	0.8013	0.7938	0.8335	0.9944
3	72	0.8569	0.8446	0.8868	0.8630	0.8507	0.8932	0.9928
4	56	0.9176	0.9335	0.9802	0.9241	0.9400	0.9870	0.9931
1	72	0.8637	0.8513	0.8939	0.8799	0.8673	0.9107	0.9816
2	71	0.8493	0.8651	0.9084	0.8667	0.8828	0.9269	0.9800
3	70	0.8215	0.8139	0.8546	0.8365	0.8287	0.8701	0.9822
4	56	0.8560	0.8708	0.9143	0.8702	0.8853	0.9296	0.9835
1	70	0.8936	0.8853	0.9296	0.8691	0.8610	0.9041	1.0282
2	72	0.7917	0.7804	0.8194	0.7688	0.7578	0.7957	1.0298
3	71	0.9075	0.9244	0.9706	0.8870	0.9035	0.9487	1.0231
4	56	0.9112	0.9270	0.9734	0.8882	0.9036	0.9488	1.0259
MEAN VALUE ➡		0.8697	0.8729	0.9165	0.8693	0.8724	0.9160	1.0007

Table 6.1.6:  
 Results - Site 3 - Wall type A




SENSOR SERIAL NO:	POSITION MAT	P1	P2	P3	P4	P5	P6
71	M1	1.0441	0.9269	0.9487			
70	M2	0.9041	0.8335	0.8701			
72	M3	0.9107	0.7957	0.8932			
56	M4				0.9870 0.9296 0.9488		
	M5						
	M6						
MEAN		0.9530	0.8520	0.9040	0.9551		

Table 6.1.7:  
Results - Matrix format - Site 3 - Wall type A



START DATE: 08/03/89
END DATE: 20/03/89
DURATION: 12 DAYS
LOCATION:
N. TYNESIDE HOSPITAL - (RESIDENCE)
RECORDING INSTRUMENT / No.
H / 74
WALL CONSTRUCTION:
OUTER LEAF: DESFORD BRICK
INSULATION: YES (SEE "POLYBLOX")
INNER LEAF: "POLYBLOX" BLOCK
FILE NAME: NTB9WLT.001
COMMENTS:
N. TYNESIDE HOSPITAL - BLOCK 9 3 EXTRA SERIES OF MEASUREMENTS ON THE 1st FLOOR FLAT. 1st SERIES. TOP LEFT HFS OUT OF 4 HFS's.
BUILDING SCIENCE SECTION SCHOOL OF ARCHITECTURE NEWCASTLE UNIVERSITY

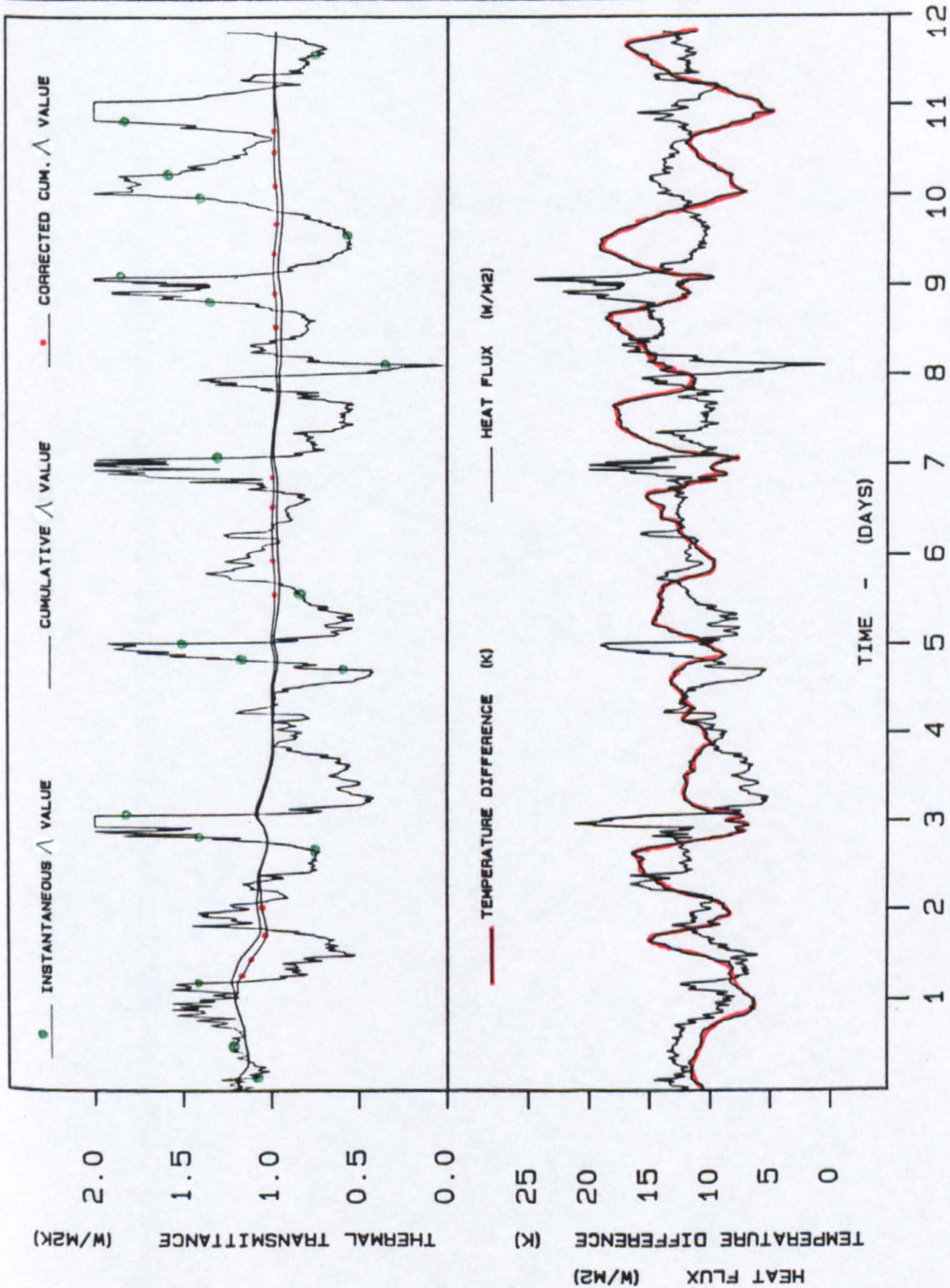


Fig. 6.1.10: Indicative sample of temperature difference, heat flux, instantaneous  $\Lambda$  value, cumulative (Averaging)  $\Lambda$  value, corrected (Anderson)  $\Lambda$  value for Site 3 - Wall type A



## WALL TYPE B

### CASE STUDY 2

CONSTRUCTION: BRICK/UNFILLED CAVITY/BLOCK/PLASTER

LOCATION: NORTH TYNESIDE HOSPITAL  
PSYCHIATRY BLOCK

No. OF SITES: 1

SITE 1: NORTH TYNESIDE HOSPITAL  
PSYCHIATRY BLOCK

No. of unique measurement points: 5

No. of multiple measurements: 13



## **6.2 An evaluation of the performance of unfilled cavity walls (Wall type B)**

Lightweight blocks are widely used in the inner leaf as a form of construction aiming to conform to the Building Regulations. The performance of the wall is evaluated by using the same procedure outlined in 6.0.1.

### **6.2.0 The measurement (Site 1)**

Thirteen measurements were undertaken at Site 1 which consisted of 5 rooms on the 1st floor of a new extension at N. Tyneside Hospital (Psychiatry Block). The wall was of brick/cavity/lightweight block/plaster construction. Table 6.2.1 gives the properties of the wall construction and a section of the wall is illustrated in Fig. 6.2.1. The location of the measurement positions was determined by the availability of space on the wall surface (which was rather restricted with the rooms concerned being small offices) and the requirement to place the sensors on a thermally uniform area of the wall. This was achieved by using the infrared camera so that thermal abnormalities on the wall could be established and avoided. The mortar joints were clearly visible with the infrared camera because of the considerably lower conductivity of the blockwork compared to the mortar.

### **6.2.1 Description of the measurement**

A series of 3 measurement periods was undertaken. All HFSs were placed at approximately the same position on the wall surface in each separate room (Fig. 6.2.2). The measurement positions were at 5 separate rooms in the same north facing wall (Fig. 6.2.3). Four HFSs were placed at the centre of the block (at Positions 1, 2, 4 and 5) and 1 HFS (corresponding to Position 3) was placed on a horizontal mortar joint, so that the effect of the cold bridge could be examined. The HFS at Position 5 was retained in the same position throughout the 3 monitoring periods (Fig. 6.2.4). The remaining HFSs were rotated between the four positions according to the pattern shown in Fig. 6.2.4. The duration of each monitoring period was approximately 13 days.

### **6.2.2 The measured performance of the wall**

The measured wall performance is detailed in Table 6.2.2 and presented in a matrix form in Table 6.2.3.



The corrections applied to the measured values were; firstly, the term for the "relative" calibration of the HFSs and secondly a correction of +5.20%, to allow for the heat flow distortion, calculated using Trethowen's correlation (chapter 5 - section 5.1.2).

Fig. 6.2.5 shows the temperature difference, the heat flux through the wall, the instantaneous  $\Lambda$  value, the Averaging and the Anderson cumulative  $\Lambda$  values for a representative measurement point (1st monitoring period - Position 2 - Site 1).

The conductance values derived using the Averaging and the Anderson methods were found to be close together with the difference between any two values not exceeding 3% for any single measurement (Table 6.2.2). The Averaging method gave slightly higher estimates on average, but this was less than 1%. Given the high correlation between the two values ( $R=0.9995$ ) in the following analysis, the Anderson values are taken as the appropriate measure of the wall transmittance.

Focusing on Position 5 where the HFS was retained at the same position throughout the 3 monitoring periods, the successive measurements were 0.7031, 0.7184 and 0.7103 respectively and indicate that the  $\Lambda$  value was highly stable with time. The mean value was 0.7106 with a variation of less than 2.2% from the minimum value of 0.7031 to the maximum of 0.7184 (Table 6.2.3).

Analysis of Variance was carried out for the 4 sensors that were rotated (S/Table 6.2.1). This indicates that the differences between the sensors and between the wall positions were significant at the 0.044 and 0.000 level respectively.

The best estimate of the average wall performance for the 3 measurement positions (at the centre of the block) is 0.6897, 0.6191 and 0.7345 respectively with a mean value of 0.6722 and a standard error of the mean of 2.3%. There is a variation of some 25.5% between the upper (0.7382) and lower (0.5649) estimates of the measured wall performance.

The effect of the mortar joint is to increase the transmittance of the wall to 1.0492 compared to the centre of the block which has a mean value of 0.6722 (excluding Position 5), an increase of 56% (Table 6.2.3).

The main effects of position and sensor explain most of the variation within the measurement set with the mean square of the residual or unexplained variance due to all factors other than the sensors and the positions being  $0.25 \times 10^{-3}$ . This gives an indication of the random error introduced by the attachment of the sensors on the wall and to all other random sources of variation in the measurement process while the standard error associated with a single transmittance measurement is given by:

( $\sqrt{\text{residual value/mean sample value}}$ ) =  $\sqrt{0.25 \times 10^{-3}}/0.7853$   
 and gives a value of 2.0% for 3 degrees of freedom.

SOURCE OF VARIATION	SUM OF SQUARES (10 <sup>-3</sup> )	DF	MEAN SQUARE (10 <sup>-3</sup> )	F	SIGNIF. OF F
Main Effects	323.01	6	53.83	213.210	0.000
Sensor	7.79	3	2.60	10.286	0.044 significant
Position	278.79	3	92.93	368.044	0.000 significant
Residual	0.76	3	0.25		
Total	323.77	9	35.97		
where F = mean square value/residual value					
<i>S/</i> Table 6.2.1: <i>Analysis of Variance for Site 1 results for all rotating sensors - Wall type B</i>					

### 6.2.3 Determination of the theoretical performance of the wall

The following models were used to calculate the theoretical performance of the wall:

- (1) the CIBSE 1D model
- (2) the CIBSE area weighted model
- (3) finite element model

#### CIBSE 1D model:

The  $\Lambda$  value was calculated according to the CIBSE Guide which assumes homogeneous construction by taking into account the thermophysical properties of each separate layer comprising the wall. The best estimate of the  $\Lambda$  value was 0.65 W/m<sup>2</sup>K using the values in Table 6.2.4.



**CIBSE area weighted model:**

The area weighted model was also used in order to take into account the effect of the mortar joints. The best estimate of the  $\Lambda$  value is therefore 0.77 W/m<sup>2</sup>K for a 10mm mortar joint and a block of standard dimensions 440 \* 215 \* 100 mm. The proportions for the block and mortar area was taken as 93.43% and 6.56% respectively.

**Finite element model:**

In order to achieve a better approximation, an additional set of calculations was carried out i.e. a 3D finite element model was applied. Two estimates are presented for the  $\Lambda$  value of the lightweight block wall, a block average value of 0.78 and a block centre value of 0.66. The block average value considers the heat flow through the total surface of the block including the mortar joints. The data used are given in Table 6.2.4.

The wall surface resistances (m<sup>2</sup>K/W) were also taken as:

Internal	Cavity	External
0.123	0.09	0.03

Ident: Wall Type B		
Material	Thickness (mm)	Resistance (m <sup>2</sup> K/W)
Brick	100	0.122
Cavity	65	
Insulation	None	
Block	150	1.150
Plaster	13	0.110
Mortar joint	150	0.125
Table 6.2.4: Construction details used for thermal modelling - Site 1 - Wall type B		

6.2.4 Comparison between the measured and theoretical transmittance values

The values obtained are shown in Table 6.2.5.

	FE Model ling	CIBSE Guide 1D	Area Weighted	Measured value
Block average	0.78	X	0.77	
Block centre	0.66	0.65	X	0.67
Mortar joint				1.05
Block average/ Block centre	1.18		1.18	
<b>Table 6.2.5:</b> <i>FE, CIBSE and measured transmittance values (W/m<sup>2</sup>K) for a brick/cavity/lightweight block/plaster wall - Site 1 - Wall type B</i>				

The CIBSE 1D model assumes homogeneous construction and is expected to be a good estimate of the block centre value. A reasonable correspondence with the FE block centre value is anticipated. The measured value at the block centre is also expected to be in agreement with the theoretical values. This in fact is the case with the FE, CIBSE 1D block centre and the measured values being 0.66, 0.65 and 0.67 respectively.

Given the experimental errors and the uncertainty in calculating the theoretical performance due to possible differences in material properties and dimensions between the actual and theoretical walls, there is a suprisingly good agreement for the block centre values. The CIBSE 1D value (chapter 4) and the mean of the measured values may both be considered to have a typical uncertainty limit of +/-4.2%.

On the other hand the CIBSE area weighted model which takes into account the cold bridging is expected to be a good estimate of the block average and a reasonable correspondence with the FE block average is anticipated. Again this is the case where both models give consistent results with the CIBSE area weighted and the FE values being 0.77 and 0.78 respectively.



The average block performance is greater than the block centre due to the bridging effect of the mortar joint. The measured value lies between the upper and lower limits of the calculated block average and block centre values (Table 6.2.5).

From the measured data, the best estimate of the average wall performance to take the bridging effect into account, is to take the ratio of the FE average to the FE block centre value of 1.18 and to multiply by the measured centre block value. This gives a result of 0.79 which is in close agreement with the FE and CIBSE block average values.

The estimated value of 0.79 compares favourably to the average of 0.87, for the mortar joint position (1.05) and the block centre (0.69). While this can only be viewed as an approximate estimate it does give increased confidence in the measured values.

The effect of the mortar joint on the average performance of the wall is clear from Table 6.2.5 for this particular type of construction where the mortar joint with a conductivity of 0.8 W/mK forms a highly conductive path for the heat flow as opposed to the very much lower conductivity of the aerated block of 0.13 W/mK.

Analysis of Variance indicated that there are significant differences between the wall positions at the centre of the blocks selected for the measurement (S/Table 6.2.1). While every effort was made for the sensors to be placed at the centre of the block and a reasonable agreement between these values had been expected, there was still a considerable variation - 25.5% - over the values measured. This variability gives rise to a 99% confidence limits on the mean for the 3 positions at the block centres of +/-6.9%.

The variation to be expected due to changes in the material properties and dimensional tolerances of the wall is +/-4.2%, a range of 8.4%, calculated according to the Pentz and Shott method (chapter 4). The value of 25.5% is slightly greater and implies that additional factors may be contributing to the variability of the  $\Lambda$  values. For example, the measurements were carried out in different blocks in different non-adjacent rooms/walls, the possible presence of protrusions into the cavity airspace.

In addition, thermographic analysis also indicated a 0.3 to 0.5 °C temperature gradient across the face of the block for all 3 positions where the HFSs were placed at the centre of the block. The causes for this may include temperature stratification, complex 3D heat flow effects taking place within the blockwork layer, cold bridges (highly conductive heat flows), different standards of workmanship (different teams of workers building different rooms/walls).

As in the case of the "Polyblox" wall, it is not possible to distinguish whether the resulting 25.5% variation in the measured values across the 3 positions is due to the wall or due to the combined effect of a number of causes that were outlined above.

Despite of this variability there is some evidence to suggest that this wall behaves according to its theoretical capabilities. If the value resulting from the CIBSE 1D model which is traditionally employed as a design tool, is compared with the estimated measured value, it seriously underestimates the average performance of the wall. From this study the best estimate for the measured average wall performance is 0.79 which is in close agreement with the CIBSE area weighted value of 0.77 and the FE block average value of 0.78.



**SITE 1**

**WALL DETAILS**

**PHYSICAL DESCRIPTION**

**OF**

**THE WALL**

**AND**

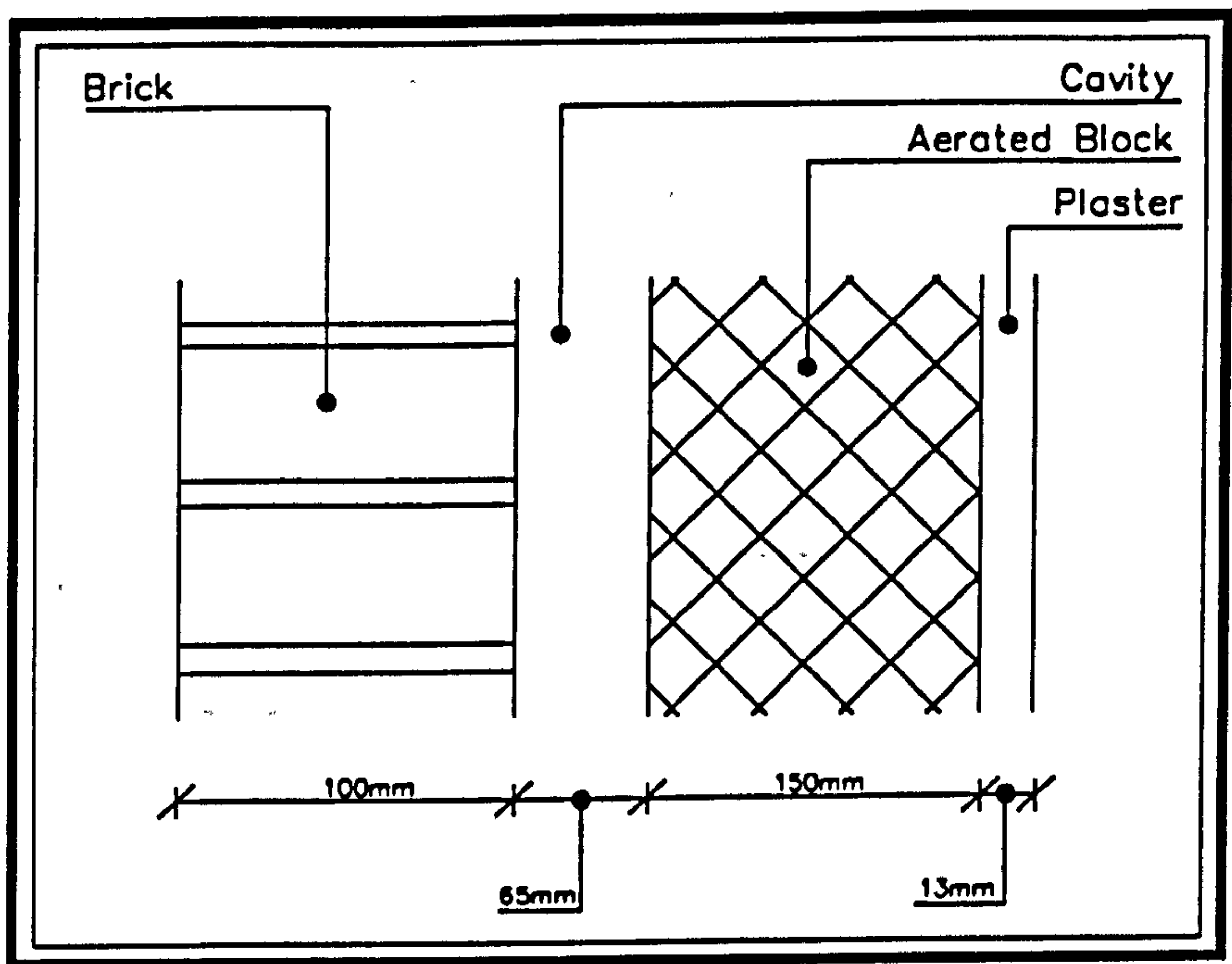
**LOCATION OF HFSs**

<div style="border: 1px solid black; padding: 2px;"> ID: WALL TYPE B </div>	<h2 style="margin: 0;">PROPERTIES OF WALL CONSTRUCTION</h2>																												
<p><b>SITE:</b> NORTH TYNESIDE HOSPITAL - NEW PSYCHIATRY BLOCK (PHASE 2)</p> <p>SITE No.:                      SERIES OF MEASUREMENT:                      DATE: WINTER 89</p> <p>CONSTRUCTION YEAR: 1987                      FILENAME:</p>																													
<p><b>INNER LEAF: AERATED CONCRETE BLOCK</b></p> <table style="width: 100%; margin-top: 10px;"> <tr><td>PLASTER .....</td><td>YES</td></tr> <tr><td>DENSITY (Kg/m<sup>3</sup>) .....</td><td>500</td></tr> <tr><td>PLASTER DENSITY .....</td><td>700</td></tr> <tr><td>DENSITY (mean) .....</td><td>515</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) .....</td><td>1000</td></tr> <tr><td>PLASTER SPECIFIC HEAT CAPACITY .....</td><td>800</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) .....</td><td>1000</td></tr> <tr><td>THICKNESS (m) .....</td><td>0.150</td></tr> <tr><td>PLASTER THICKNESS .....</td><td>0.013</td></tr> <tr><td>THICKNESS (total) .....</td><td>0.163</td></tr> <tr><td>CONDUCTIVITY (W/mK) .....</td><td>0.13</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) .....</td><td>1.150</td></tr> <tr><td>PLASTER RESISTANCE .....</td><td>0.110</td></tr> <tr><td>RESISTANCE (total) .....</td><td>1.260</td></tr> </table>		PLASTER .....	YES	DENSITY (Kg/m <sup>3</sup> ) .....	500	PLASTER DENSITY .....	700	DENSITY (mean) .....	515	SPECIFIC HEAT CAPACITY (J/KgK) .....	1000	PLASTER SPECIFIC HEAT CAPACITY .....	800	SPECIFIC HEAT CAPACITY (mean) .....	1000	THICKNESS (m) .....	0.150	PLASTER THICKNESS .....	0.013	THICKNESS (total) .....	0.163	CONDUCTIVITY (W/mK) .....	0.13	RESISTANCE (m <sup>2</sup> K/W) .....	1.150	PLASTER RESISTANCE .....	0.110	RESISTANCE (total) .....	1.260
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<p><b>OUTER LEAF: TILCON LIGHT MULTI-RUSSET FACING BRICK</b></p> <table style="width: 100%; margin-top: 10px;"> <tr><td>RENDER ? .....</td><td>NO</td></tr> <tr><td>DENSITY (kg/m<sup>3</sup>) .....</td><td>1885</td></tr> <tr><td>RENDER DENSITY .....</td><td></td></tr> <tr><td>DENSITY (mean) .....</td><td>1885</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) .....</td><td>790</td></tr> <tr><td>RENDER SPECIFIC HEAT CAPACITY .....</td><td></td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) .....</td><td>790</td></tr> <tr><td>THICKNESS (m) .....</td><td>0.1</td></tr> <tr><td>RENDER THICKNESS .....</td><td></td></tr> <tr><td>THICKNESS (total) .....</td><td>0.1</td></tr> <tr><td>CONDUCTIVITY (W/mK) .....</td><td>0.82</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) .....</td><td>0.122</td></tr> <tr><td>RENDER RESISTANCE .....</td><td></td></tr> <tr><td>RESISTANCE (total) .....</td><td>0.122</td></tr> </table>		RENDER ? .....	NO	DENSITY (kg/m <sup>3</sup> ) .....	1885	RENDER DENSITY .....		DENSITY (mean) .....	1885	SPECIFIC HEAT CAPACITY (J/KgK) .....	790	RENDER SPECIFIC HEAT CAPACITY .....		SPECIFIC HEAT CAPACITY (mean) .....	790	THICKNESS (m) .....	0.1	RENDER THICKNESS .....		THICKNESS (total) .....	0.1	CONDUCTIVITY (W/mK) .....	0.82	RESISTANCE (m <sup>2</sup> K/W) .....	0.122	RENDER RESISTANCE .....		RESISTANCE (total) .....	0.122
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CAVITY RESISTANCE: 0.180	INSULATION RESISTANCE:																												
HFS No.	HFS CALIBRATION FACTOR:																												

**Table 6.2.1:**

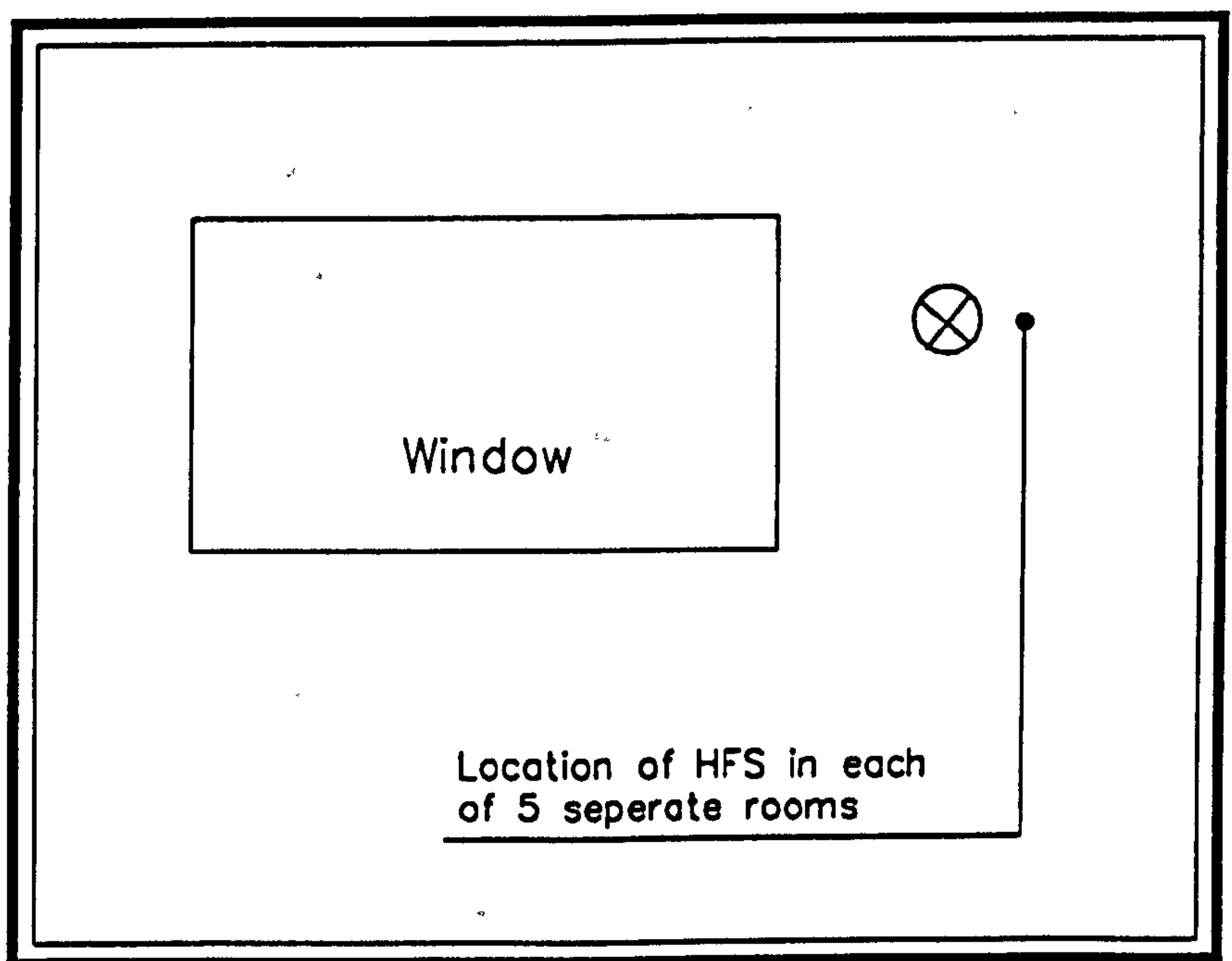
*Properties of wall construction - Site 1 - Wall type B*





**Fig. 6.2.1:**

*Section through the wall construction - Site 1 - Wall type B*



**Fig. 6.2.2:**

*Position of HFSs on the wall surface - Site 1 - Wall type B*

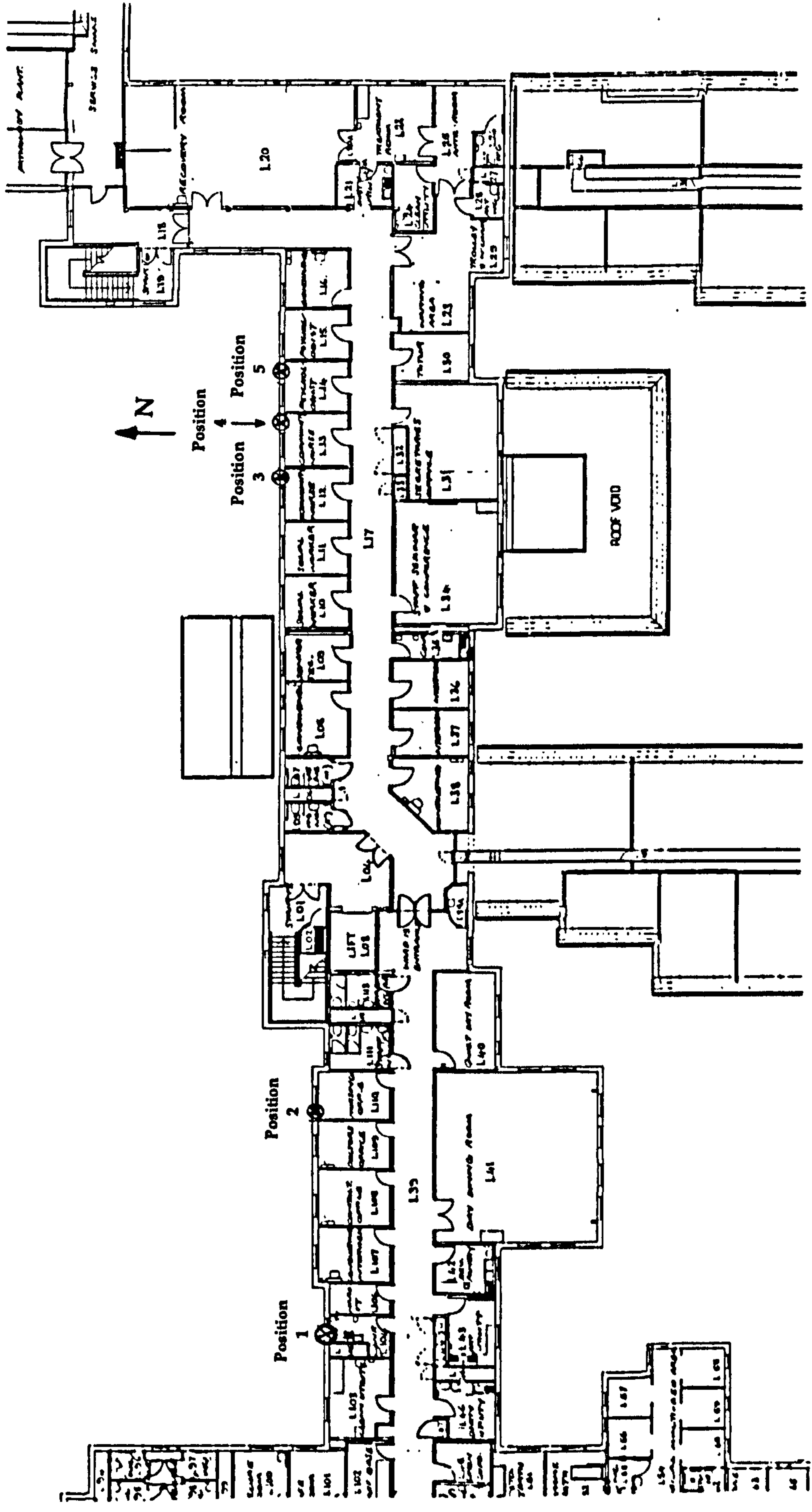



Fig. 6.2.3:  
Location of HFSs on the wall surface - Plan view - Site 1 - Wall type B



**SITE 1**

**DATA ANALYSIS**

	P1	P2	P3	P4	P5
M1	1	2			
M2	3	1	2		
M3		3	1	2	
M4			3	1	
M5					1

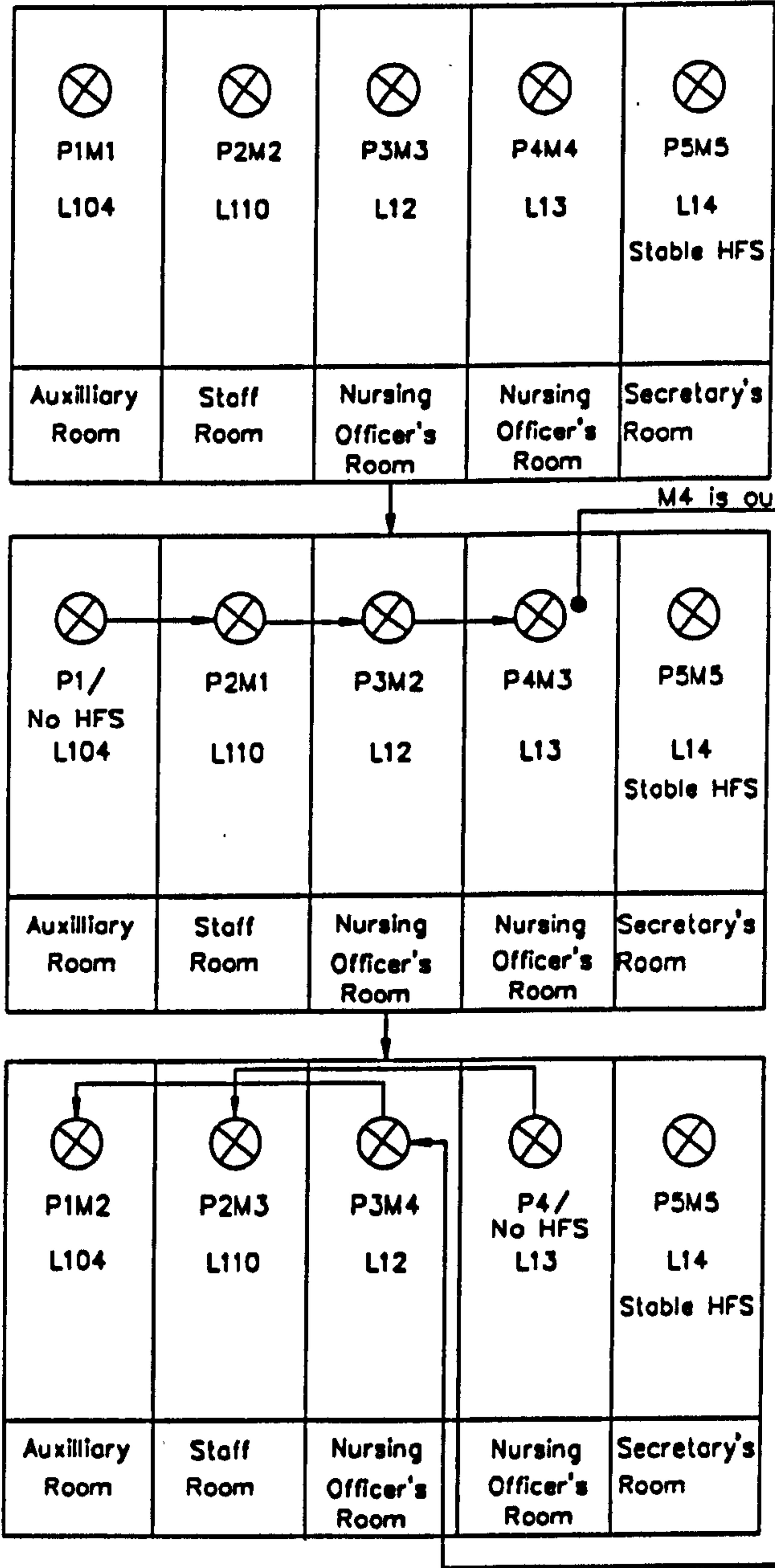


Fig. 6.2.4:  
HFSs rotation pattern - Site 1 - Wall type B



Position	Sensor No:	Averaging Method $\Lambda$ Value			Anderson Method $\Lambda$ Value			Averaging Corrected Value <div>Anderson Corrected Value</div>
		Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	
1	71	0.6799	0.6925	0.7285	0.6749	0.6875	0.7233	1.0072
2	72	0.6151	0.6063	0.6378	0.6089	0.6002	0.6314	1.0101
3	70	0.9807	0.9716	1.0221	0.9773	0.9682	1.0185	1.0035
4	56	0.6933	0.7053	0.7420	0.6898	0.7017	0.7382	1.0051
5	67	0.6853	0.6757	0.7108	0.6778	0.6683	0.7031	1.0110
2	71	0.6157	0.6272	0.6598	0.6167	0.6282	0.6609	0.9983
4	70	0.7209	0.7142	0.7513	0.7012	0.6947	0.7308	1.0281
5	67	0.6973	0.6875	0.7233	0.6926	0.6829	0.7184	1.0068
3	72	1.0435	1.0286	1.0821	1.0293	1.0146	1.0674	1.0138
5	67	0.6873	0.6777	0.7129	0.6848	0.6752	0.7103	1.0037
3	56	0.9961	1.0133	1.0660	0.9919	1.0091	1.0616	1.0041
2	70	0.5467	0.5416	0.5698	0.5420	0.5370	0.5649	1.0087
1	72	0.6429	0.6337	0.6667	0.6327	0.6237	0.6561	1.0162
MEAN VALUE ➡								1.0095

Table 6.2.2:  
 Results - Site 1 - Wall type B


SENSOR SERIAL NO:	POSITION MAT	CENTRE OF P1 THE BLOCK	CENTRE OF P2 THE BLOCK	MORTAR P3 JOINT	CENTRE OF P4 THE BLOCK	CENTRE OF P5 THE BLOCK	P6
71	M1	0.7233	0.6609				
72	M2	0.6561	0.6314	1.0674			
70	M3		0.5649	1.0185	0.7308		
56	M4			1.0616	0.7382		
67	M5					0.7031 0.7184 0.7103	
	M6						
MEAN		0.6897	0.6191	1.0492	0.7345	0.7106	

Table 6.2.3:  
Results - Matrix format - Site 1 - Wall type B



START DATE: 19/01/89
END DATE: 01/02/89
DURATION: 13 DAYS
LOCATION: N. TYNESIDE HOSPITAL - (PSYCHIATRY)
RECORDING INSTRUMENT / No.
H / 72
WALL CONSTRUCTION: OUTER LEAF: TILCON FACING BRICK INSULATION: NO INNER LEAF: AER. CONCRETE BLOCK
FILE NAME: NTPL110.001
COMMENTS: N. TYNESIDE HOSPITAL - PSYCHIATRY ROOM L110 - 1st SERIES - WINTER 1989 1 OUT OF 5 HFS'S, EACH PLACED IN A DIFFERENT ROOM.
BUILDING SCIENCE SECTION SCHOOL OF ARCHITECTURE NEWCASTLE UNIVERSITY

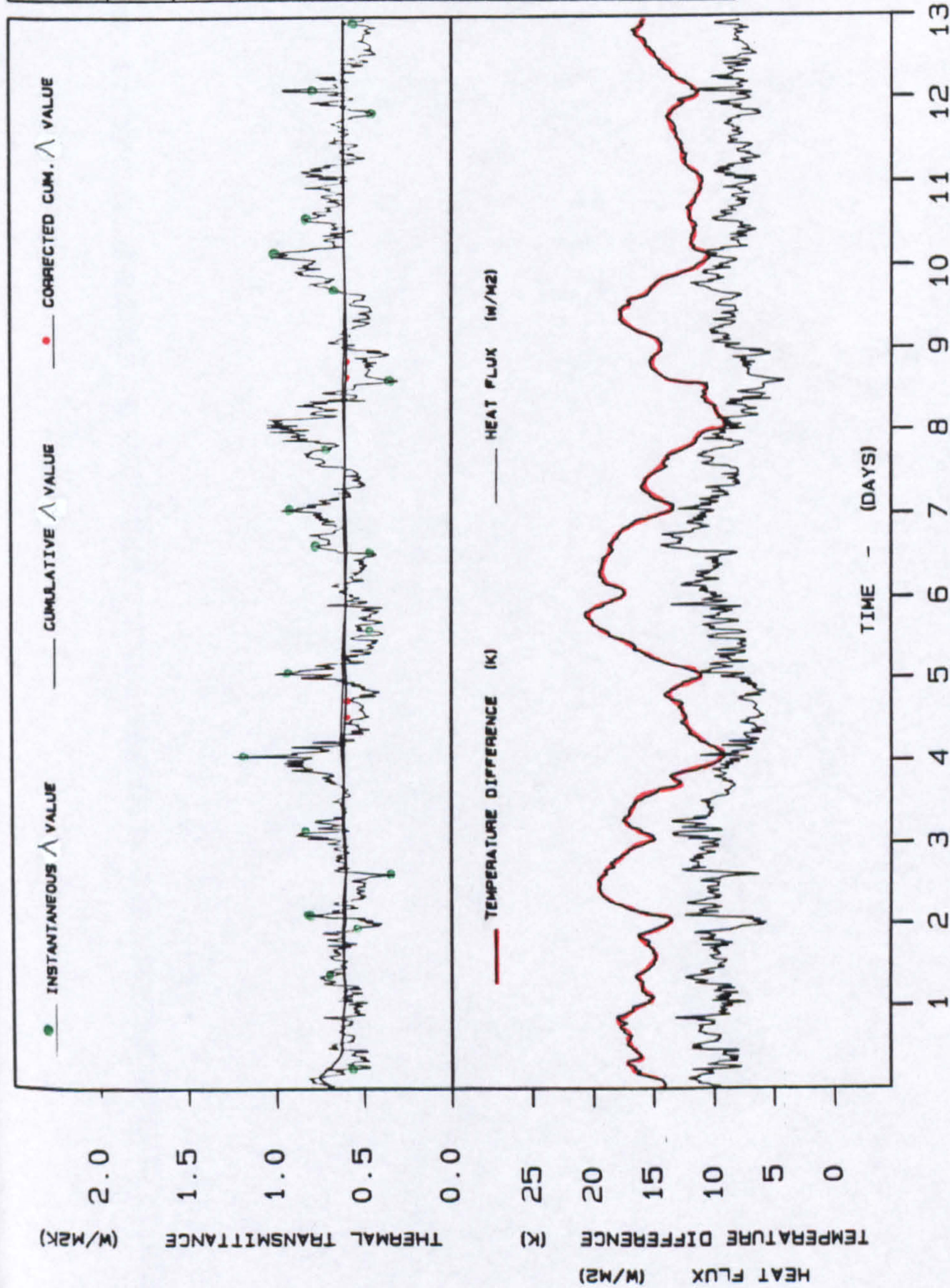


Fig. 6.2.5:

Indicative sample of temperature difference, heat flux, instantaneous  $\Lambda$  value, cumulative (Averaging)  $\Lambda$  value, corrected (Anderson)  $\Lambda$  value - Site 1 - Wall type B



## WALL TYPE C

### CASE STUDIES 3 & 4

CONSTRUCTION: BRICK/PARTIALLY FILLED CAVITY/  
BLOCK/PLASTER

LOCATION: CRAMLINGTON - BURNSIDE SCHOOL  
(CASE STUDY 3)

BLYTH - WENSLEYDALE SCHOOL  
(CASE STUDY 4)

No. OF SITES: 2

SITE 1: CRAMLINGTON - BURNSIDE SCHOOL  
(STAFF ROOM/LIBRARY)

No. of unique measurement points: 6

No. of multiple measurements: 16

SITE 2: BLYTH - WENSLEYDALE SCHOOL  
(CLASSROOMS)

No. of unique measurement points: 2

No. of multiple measurements: 4



### **6.3/4 An evaluation of the performance of a partially filled cavity wall (Wall type C)**

A layer of insulation in the cavity airspace is an effective means of decreasing the heat losses through the wall fabric to a considerable extent. The performance of the wall is evaluated by using the same procedure outlined in 6.0.1. Twenty measurements were undertaken at two Sites, Site 1 and Site 2.

#### **6.3.0 The measurement (Site 1)**

Sixteen measurements were undertaken at Site 1 which consisted of 2 rooms at the ground floor at Burnside First School - Cramlington. The wall was of brick/partially filled cavity/hollow block/plaster construction. The 75mm wall cavity was partially insulated with a 40mm Jablite rigid board (lightweight closed-cell material made from expanded polystyrene of 0.037 W/mK conductivity). The hollow block in this case is a Forticrete hollow block, with two voids, open at the two ends (Forticrete - 1985). Table 6.3.1 gives the properties of the wall construction and a section of the wall is illustrated in Fig. 6.3.1.

The location of the measurement positions was determined by the availability of space on the wall surface and the requirement to place the sensors on a thermally uniform area of the wall. This was achieved by using the infrared camera so that thermal abnormalities on the wall could be established. Areas of nearly uniform temperature field were identified as well as areas of gross defects in the insulation system. The mortar joints were not visible with the infrared camera, due to the presence of the insulation layer in the cavity airspace forming the major part of the total resistance of the wall structure. With the resolution of the infrared camera it was not possible to define on-site the voids in the block, therefore, it is not known whether the sensor was placed at the centre of the block or at the centre of the void or in between.

#### **6.3.1 Description of the measurement**

A series of 3 measurement periods was undertaken. The HFSs were placed on the wall surface at the positions shown in Fig. 6.3.2. There were 6 measurement positions in 2 separate rooms (the staff room and the library), on the same north wall (Fig. 6.3.3).

It was possible to clearly define two cold bridge spots with the infrared camera (Positions 1 and 5). The sensors were placed in the locality of the cold bridge spots to compare these results with the results from the other 4 positions in order to establish the magnitude of the failure of the insulation system.

Four HFSs were placed in the staff room (at Positions 1 to 4) and two HFSs (corresponding to Positions 5 and 6) were placed in the library. The HFS at Position 6 was retained in the same position throughout the 3 monitoring periods. The remaining HFSs were rotated between the five positions according to the pattern shown in Fig. 6.3.4. The duration of each monitoring period was approximately 14 days.

### 6.3.2 The measured performance of the wall

The measured wall performance is detailed in Table 6.3.2 and presented in a matrix form in Table 6.3.3.

The corrections applied to the measured values were; firstly, the term for the "relative" calibration of the HFSs and secondly a correction of +5%, to allow for the heat flux distortion, calculated using Trethowen's correlation (chapter 5 - section 5.1.2).

Fig. 6.3.5 shows the temperature difference, the heat flux through the wall, the instantaneous  $\Lambda$  value, the Averaging and the Anderson cumulative  $\Lambda$  values for a representative measurement point (2nd monitoring period - Position 4 - Site 1).

The conductance values derived using the Averaging and the Anderson methods were found to be close together with the difference between any two values not exceeding 5.6% for any single measurement (Table 6.3.2). The Averaging method gave slightly higher estimates on average, but this was less than 2.3%. Given the high correlation between the two values ( $R=0.9882$ ) in the following analysis, the Anderson values are taken as the appropriate measure of the wall transmittance.

Focusing on Position 6 where the HFS was retained in the same position throughout the 3 monitoring periods, the successive measurements were 0.6084, 0.5707 and 0.5808 indicate that the T value was stable with time. The mean value for position 6 is 0.5866 with less than a 6.5% variation from the minimum value of 0.5707 to the maximum 0.6084 (Table 6.3.3).

Analysis of Variance was carried out for the 5 sensors that were rotated (S/Table 6.3.1). This indicates that the differences between the sensors and between the wall positions were significant at the 0.022 and 0.000 level respectively. There are significant differences in both; the performance of the wall at the selected positions and between the sensor sets.

The main effects of position and sensor explain most of the variation within the measurement set with the mean square of the residual or unexplained variance due to all factors other than the sensors and the positions being  $0.36 \times 10^{-3}$ . This gives an indication of the random error introduced by the attachment of the sensors on the wall and to all other



random sources of variation in the measurement process while the standard error for a single transmittance measurement is given by:

$$(\sqrt{\text{residual value}}/\text{mean sample value}) = \sqrt{0.36 \times 10^{-3}}/0.7066$$

and gives a value of 2.7% for 4 degrees of freedom.

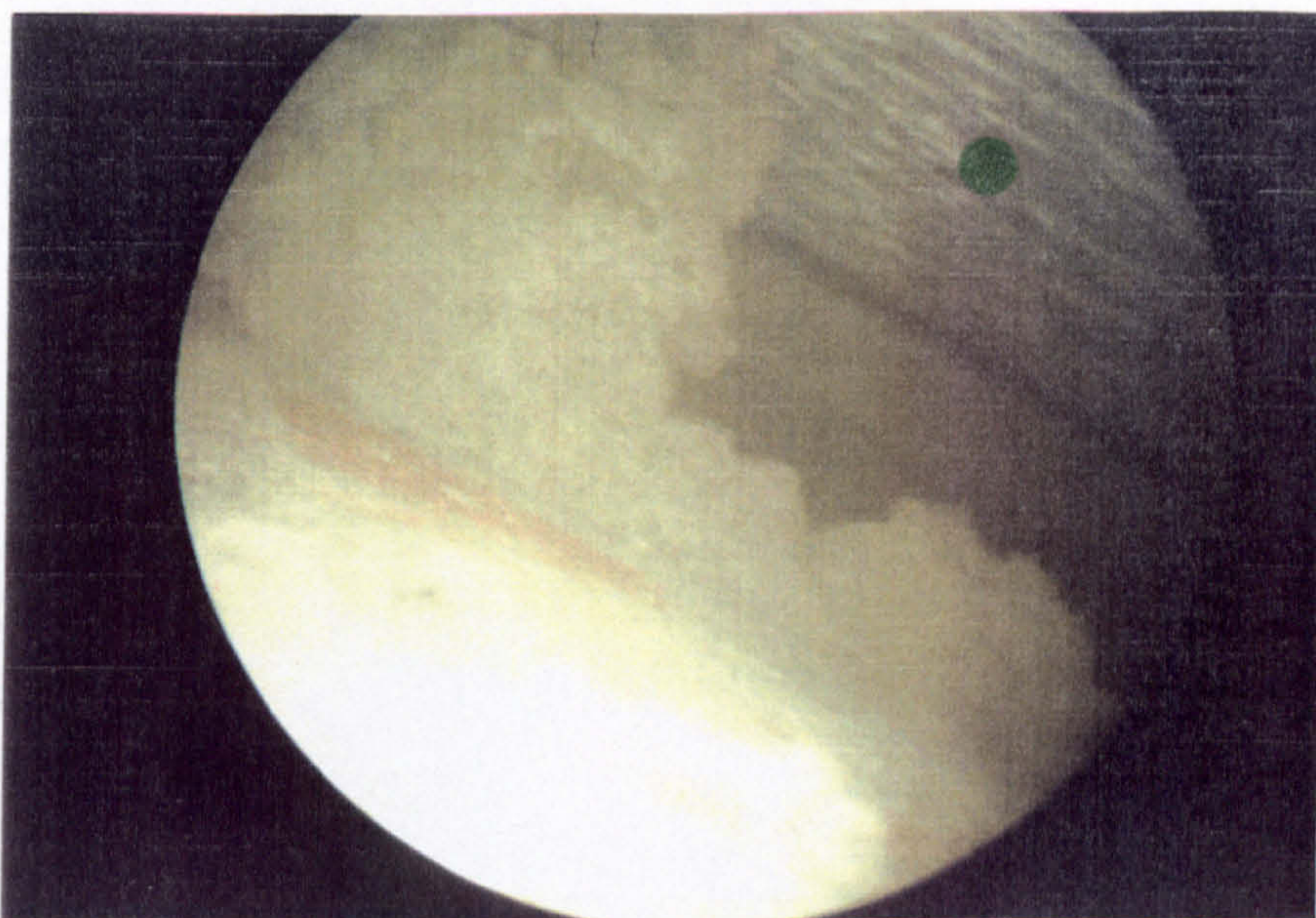
SOURCE OF VARIATION	SUM OF SQUARES (10 <sup>-3</sup> )	DF	MEAN SQUARE (10 <sup>-3</sup> )	F	SIGNIF. OF F
Main Effects	190.59	8	23.82	66.988	0.001
Sensor	14.71	4	3.68	10.343	0.022 significant
Position	159.44	4	39.86	112.081	0.000 significant
Residual	1.42	4	0.36		
Total	192.01	12	16.00		
where F = mean square value/residual value					
<i>S/Table 6.3.1:</i> <i>Analysis of Variance for Site 1 results for all rotating sensors - Wall type C</i>					

Two issues are examined in turn, the positions that indicated a thermally uniform or nearly uniform temperature field and the positions that indicated cold bridging of the insulation system.

The best estimate of the average wall performance for the 3 measurement positions (Positions 2, 3 and 4) is 0.6501, 0.6401 and 0.6305 respectively with a mean value of 0.6402 and a standard error of the mean of 0.8%. There is a difference of some 10% between the upper (0.6789) and lower (0.6138) estimates of the measured wall performance.

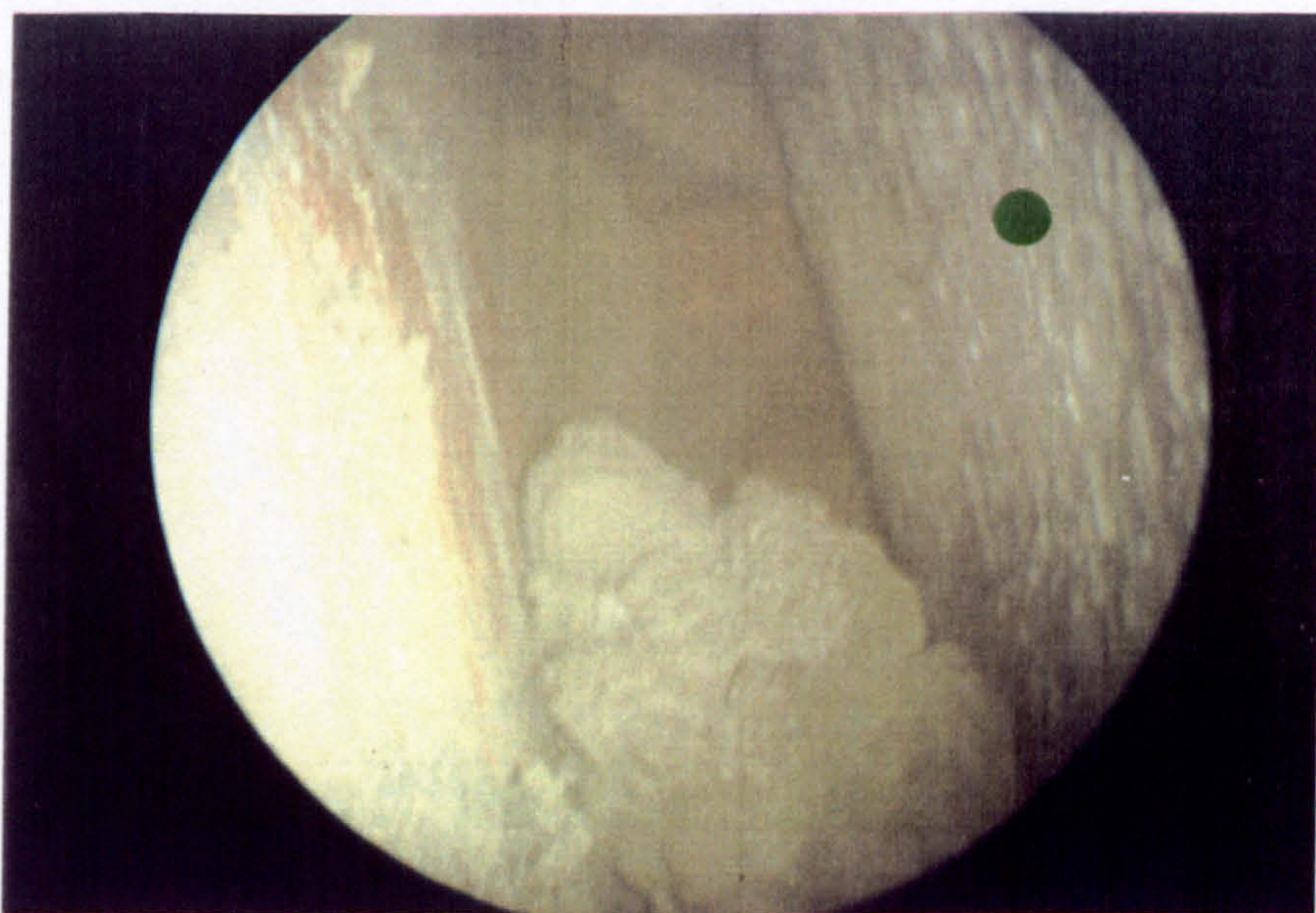
However, the  $\Lambda$  values for the areas where thermal abnormalities were defined are considerably higher. A mean  $\Lambda$  value of 0.9291 was recorded for Position 1 and 0.8187 for Position 5. The mean  $\Lambda$  value for both, Positions 1 and 5 was 0.8739. The effect of the cold bridging is to increase the transmittance of the wall from 0.6402 to 0.8739, an increase of 36.5%.





**Plate 6.3.1:**

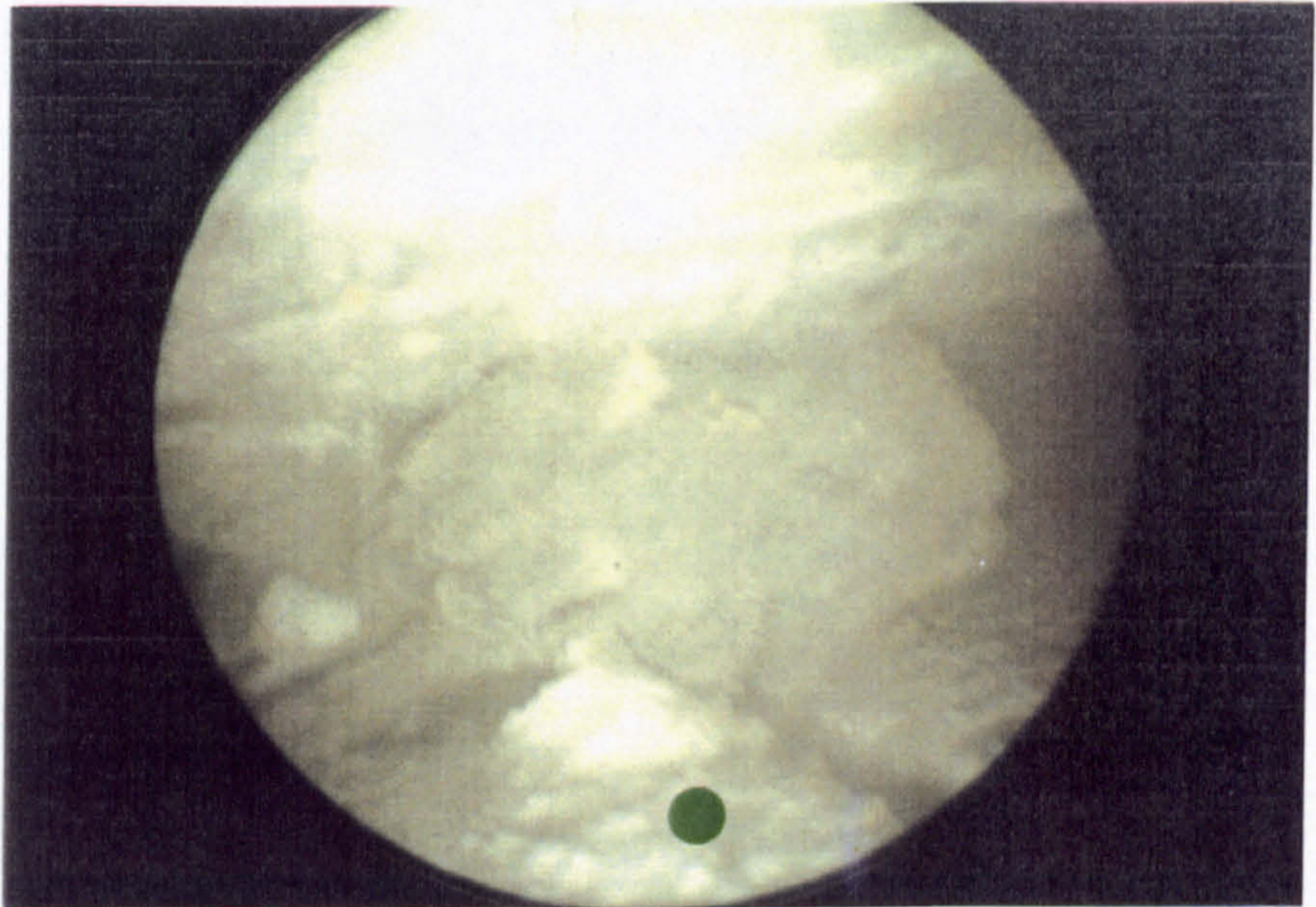
*Boroscopic examination revealed that the cavity airspace was bridged with a significant amount of mortar droppings, possibly on a wall tie, at Position 1. The green dot indicates the insulated side of the cavity.*



**Plate 6.3.2:**

*Same as for Plate 6.3.1. The bridging of the cavity airspace can clearly be seen from another angle for Position 1.*

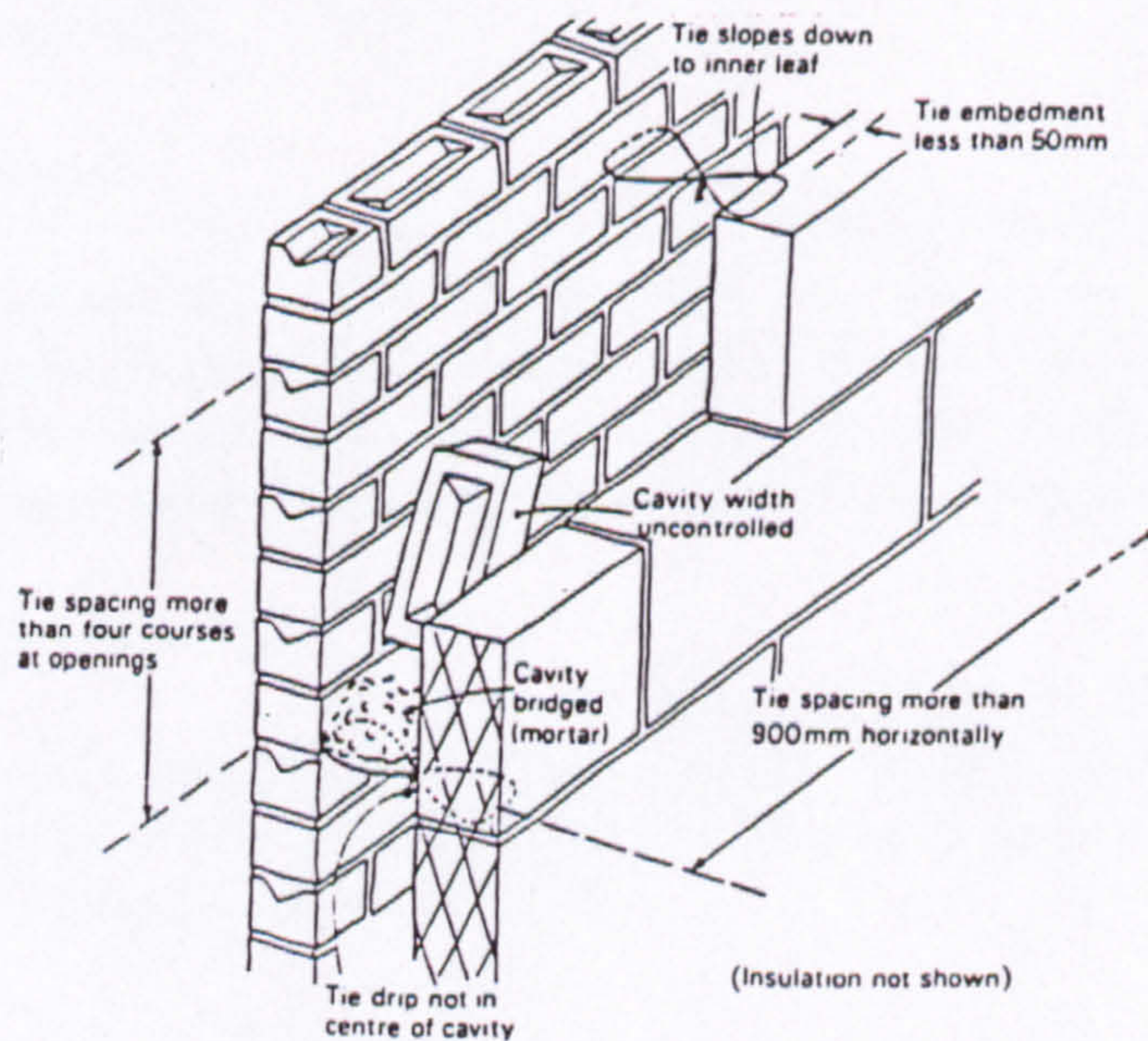




**Plate 6.3.3:**

*As with Position 1, boroscopic examination at Position 5 revealed that the cavity airspace was bridged with a significant amount of mortar droppings, possibly on a wall tie.*

*The green dot indicates the insulated side of the cavity.*



**Fig. 6.3.6:**

*Typical wall tie faults that must be avoided*

*[After Defect Action Sheet (DAS) 116 produced by BRE - June 1988]*



Boroscopic examination revealed the causes for the discrepancies. The cavity was bridged with a significant amount of mortar droppings - possibly on a wall tie - at Positions 1 (Plates 6.3.1 and 6.3.2) and 5 (Plate 6.3.3) at the place where the measurements took place. Risk of damage to the insulation material is very high in situations such as this.

Defect Action Sheet (DAS 116) produced by BRE (1988) highlights the point that wall ties bridge the cavity for structural reasons, but they must not lead water across. It continues: "if ties slope down to the inner leaf, or have drips off-centre in the cavity, or are fouled by mortar (mortar falling on wall ties must be cleaned off), rainwater can cross to the inner leaf" (Fig. 6.3.6). There is clear evidence that in this case these precautions were not taken and workmanship problems have arisen. As far as the workmanship is concerned therefore, Positions 1 and 5 indicated that recommended practice is not followed and it can seriously influence the average performance of the wall.

### **6.3.3 Determination of the theoretical performance of the wall**

The following models were used to calculate the theoretical performance of the wall:

- (1) the CIBSE 1D model
- (2) the CIBSE combined model
- (3) the Anderson model
- (4) the CIBSE area weighted model
- (5) finite element model

#### **CIBSE 1D model:**

The  $\Lambda$  value was calculated according to the CIBSE Guide which assumes homogeneous construction by taking into account the thermophysical properties of each separate layer comprising the wall. The equivalent resistance value of  $0.142 \text{ m}^2\text{K/W}$  specified by the manufacturers (Forticrete - 1985) was used for the hollow block. The best estimate of the  $\Lambda$  value was  $0.60 \text{ W/m}^2\text{K}$  using the values in Table 6.3.4.

#### **CIBSE 1D combined model:**

The combined model was also used which takes into account the voids in the block and gives the equivalent resistance of the block which in this case is  $0.432 \text{ m}^2\text{K/W}$ . The best estimate of the  $\Lambda$  value according to this model was  $0.61 \text{ W/m}^2\text{K}$  using the values in Table 6.3.4.



**Anderson model:**

The Anderson model was also used which takes into account the voids in the block and gives the total resistance of the wall construction. The best estimate of the  $\Lambda$  value according to this model was  $0.61 \text{ W/m}^2\text{K}$  using the values in Table 6.3.4.

**CIBSE area weighted model:**

The area weighted model was also used in order to take into account the effect of the mortar joints. There is no recommended practice suggested by the CIBSE Guide on the calculation of an area weighted value for walls containing slotted blocks in the inner leaf. The equivalent resistance of  $0.142 \text{ m}^2\text{K/W}$  specified by the manufacturers was therefore used. The best estimate of the  $\Lambda$  value was  $0.61 \text{ W/m}^2\text{K}$  assuming a 10mm mortar joint and a block of standard dimensions  $440 * 215 * 100 \text{ mm}$ .

**Finite element model:**

In order to achieve a better approximation, an additional set of calculations was carried out i.e. a 3D finite element model was applied. Two estimates are presented for the  $\Lambda$  value of the wall, a block average value of 0.61 and a block centre value of 0.63. The conditions applied are given in Table 6.3.4.

In the modelling process the wall surface resistances ( $\text{m}^2\text{K/W}$ ) were taken as:

Internal	Cavity	External
0.123	0.09	0.03

and the voids were treated as having a resistance of  $0.2 \text{ m}^2\text{K/W}$  as recommended by the CIBSE Guide.

<b>Ident: Wall Type C - Site 1</b>		
<b><u>Material</u></b>	<b><u>Thickness</u> (mm)</b>	<b><u>Resistance</u> (m<sup>2</sup>K/W)</b>
Brick	100	0.143
Cavity	75	
Insulation	40	1.080
Block	100	0.142
Plaster	13	0.110
Mortar joint	100	0.125
<b>Table 6.3.4:</b> <i>Construction details used for thermal modelling - Site 1 - Wall type C</i>		



6.3.4 Comparison between the measured and theoretical transmittance values

The values obtained are shown in Table 6.3.5.

	FE Mode lling	CIBSE Guide 1D	Comb. Model	Anderson Model	CIBSE G/e Area Weighted	Measured value
Block average	0.61	X	X	X	0.61	0.64
Block centre	0.63	0.60	0.61	0.61	X	X
<b>Table 6.3.5:</b> <i>FE, CIBSE and measured transmittance values (W/m<sup>2</sup>K) for a brick/partially filled cavity/hollow block/plaster wall - Site 1 - Wall type C</i>						

Table 6.3.5 indicates the consistency of the values for all models. The block centre values compare very favourably with each other. The value of 0.61 resulting from the CIBSE area weighted model is in very good agreement with the FE block average value of 0.61. The measured value of 0.64 also compares very favourably with the above values.

As expected the FE block centre value of 0.63 is slightly higher than the FE block average value of 0.61. This is attributed to the existence of a higher conductivity path through the layer in the middle of the block separating the two voids.

It is clear that the effect of the mortar joints on the average performance of the wall is negligible when insulation is included in the cavity airspace resulting in an area weighted value which is the same as the CIBSE 1D value.

Given the experimental errors and the uncertainty in calculating the theoretical performance due to possible differences in material properties and dimensions between the actual and theoretical walls, there is a suprisingly good agreement, between the measured and all the values resulting from the application of the theoretical models. The CIBSE 1D value may be considered to have a typical uncertainty limit of +/-4.3% (chapter 4), whereas the measured value has a limit of +/-4%.

In a wall construction of such a type, the insulation in the cavity is the major contributory factor to the thermal performance of the wall, in other words, the insulation layer is responsible for the majority of the temperature drop across the construction, consequently the actual temperature drop across the blockwork is minimal. It is highly unlikely that the voids could be visible by means of the infrared camera in circumstances such as the above (where there is a thermally uniform field). In that particular case, a vertical banding on the infrared monitor could just be observed on the monitor screen, which may be explained as the voids, one on top of each other forming in effect a vertical cavity. However, it has to be mentioned that the lines were very near to the edge of detection.

Analysis of Variance indicated that there are significant differences between the wall positions selected for the measurement and between the sensors (S/Table 6.3.1). However, there was good agreement between the block centre values (Positions 2, 3 and 4) with a variation of only 10%. This is in line with the variation to be expected due to changes in the material properties and dimensional tolerances of the wall calculated according to Pentz and Shott method of  $\pm 4.3\%$ , a range of 8.6%, (chapter 4) and experimental error.

Finally, the evidence is that this wall behaves according to the design specifications. The theoretical models values compare very favourably with the measured value. From this study the best estimate for the measured average wall performance is 0.64 which is in very close agreement with the CIBSE area weighted value of 0.61 and the FE block average value of 0.61. For this type of wall construction the CIBSE 1D method using manufacturers values seems to be a reliable indicator of the average performance of the wall.



**SITE 1**

**WALL DETAILS**

**PHYSICAL DESCRIPTION**

**OF**

**THE WALL**

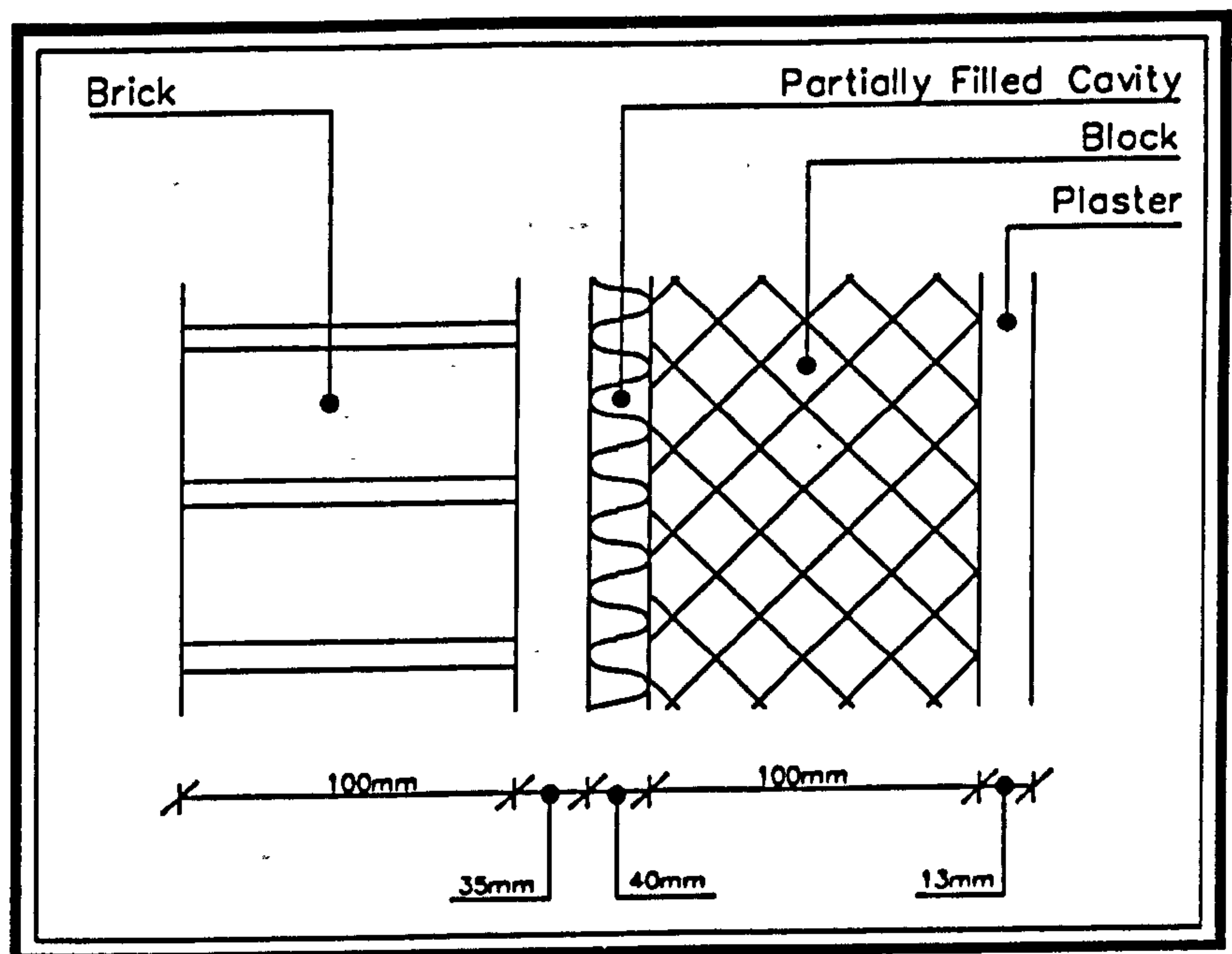
**AND**

**LOCATION OF HFSs**

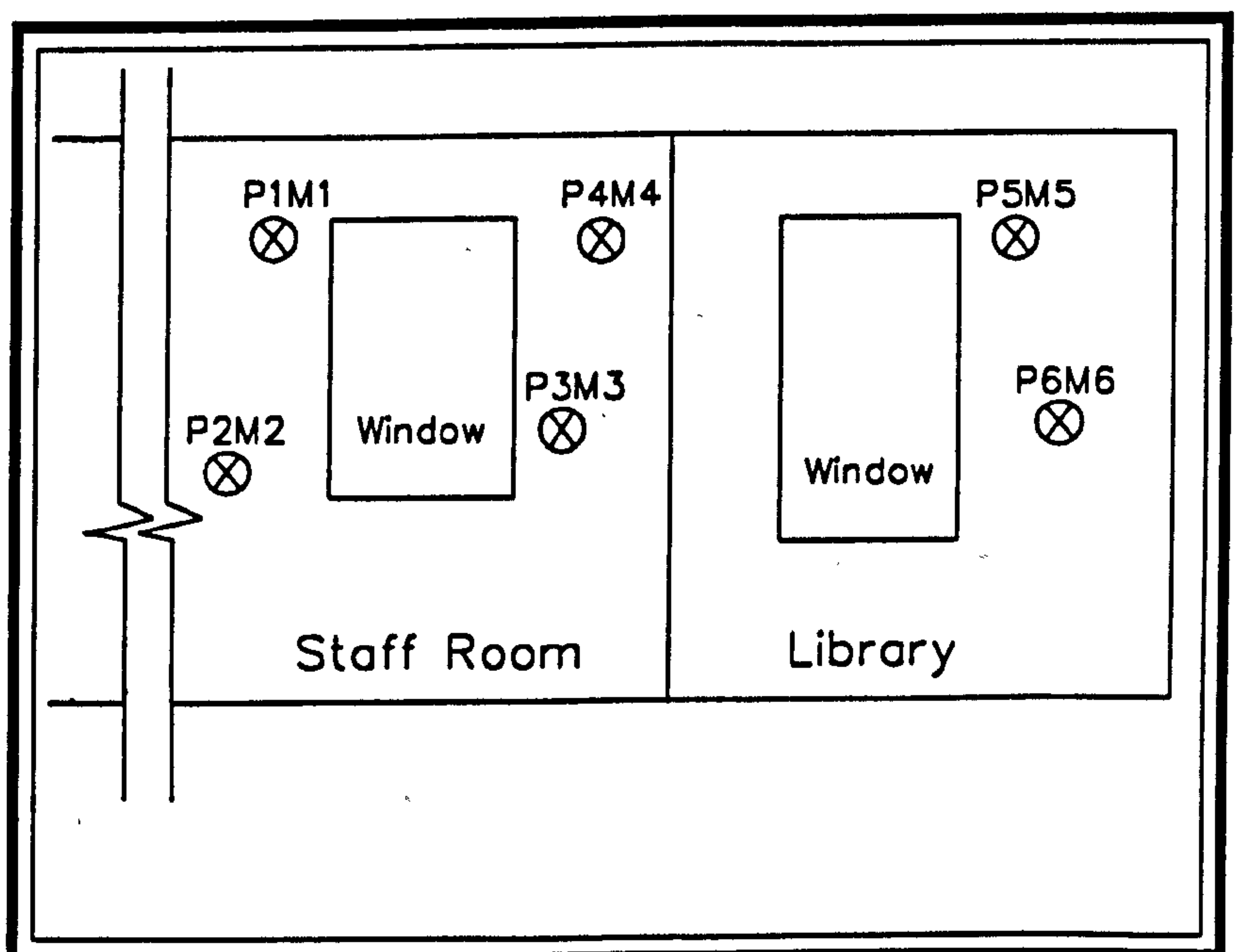
<b>ID:</b> Wall type C Site 1	<b>PROPERTIES OF WALL CONSTRUCTION</b>																												
<b>SITE:</b> CRAMLINGTON - BURNSIDE FIRST SCHOOL  <div style="display: flex; justify-content: space-between;"> <span><b>SITE No.:</b></span> <span><b>SERIES OF MEASUREMENT:</b></span> <span><b>DATE:</b> WINTER 89</span> </div> <div style="display: flex; justify-content: space-between; margin-top: 10px;"> <span><b>CONSTRUCTION YEAR:</b></span> <span><b>FILENAME:</b></span> </div>																													
<p><b>INNER LEAF:</b> CONCRETE COMMON BLOCKS - FORTICRETE HOLLOW (TWO VOIDS - OPEN AT TWO ENDS)</p> <table style="width: 100%; border-collapse: collapse;"> <tr><td style="width: 80%;">PLASTER . . . . .</td><td style="width: 20%;">YES</td></tr> <tr><td>DENSITY (Kg/m<sup>3</sup>) . . . . .</td><td>2000</td></tr> <tr><td>PLASTER DENSITY . . . . .</td><td>700</td></tr> <tr><td>DENSITY (mean) . . . . .</td><td>1850</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) . . . . .</td><td>800</td></tr> <tr><td>PLASTER SPECIFIC HEAT CAPACITY . . . . .</td><td></td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) . . . . .</td><td>800</td></tr> <tr><td>THICKNESS (m) . . . . .</td><td>0.1</td></tr> <tr><td>PLASTER THICKNESS . . . . .</td><td>0.013</td></tr> <tr><td>THICKNESS (total) . . . . .</td><td>0.113</td></tr> <tr><td>CONDUCTIVITY (W/mK) (of the concrete):</td><td>1.13</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) . . . . .</td><td>0.142</td></tr> <tr><td>PLASTER RESISTANCE . . . . .</td><td>0.110</td></tr> <tr><td>RESISTANCE (total) . . . . .</td><td>0.252</td></tr> </table>		PLASTER . . . . .	YES	DENSITY (Kg/m <sup>3</sup> ) . . . . .	2000	PLASTER DENSITY . . . . .	700	DENSITY (mean) . . . . .	1850	SPECIFIC HEAT CAPACITY (J/KgK) . . . . .	800	PLASTER SPECIFIC HEAT CAPACITY . . . . .		SPECIFIC HEAT CAPACITY (mean) . . . . .	800	THICKNESS (m) . . . . .	0.1	PLASTER THICKNESS . . . . .	0.013	THICKNESS (total) . . . . .	0.113	CONDUCTIVITY (W/mK) (of the concrete):	1.13	RESISTANCE (m <sup>2</sup> K/W) . . . . .	0.142	PLASTER RESISTANCE . . . . .	0.110	RESISTANCE (total) . . . . .	0.252
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<p><b>OUTER LEAF:</b> STOURBRIDGE BRINDLED MULTI RUSTIC FACING BRICK</p> <table style="width: 100%; border-collapse: collapse;"> <tr><td style="width: 80%;">RENDER ? . . . . .</td><td style="width: 20%;">NO</td></tr> <tr><td>DENSITY (kg/m<sup>3</sup>) . . . . .</td><td>1750</td></tr> <tr><td>RENDER DENSITY . . . . .</td><td></td></tr> <tr><td>DENSITY (mean) . . . . .</td><td>1750</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) . . . . .</td><td>790</td></tr> <tr><td>RENDER SPECIFIC HEAT CAPACITY . . . . .</td><td></td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) . . . . .</td><td>790</td></tr> <tr><td>THICKNESS (m) . . . . .</td><td>0.1</td></tr> <tr><td>RENDER THICKNESS . . . . .</td><td></td></tr> <tr><td>THICKNESS (total) . . . . .</td><td>0.1</td></tr> <tr><td>CONDUCTIVITY (W/mK) . . . . .</td><td>0.7</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) . . . . .</td><td>0.143</td></tr> <tr><td>RENDER RESISTANCE . . . . .</td><td></td></tr> <tr><td>RESISTANCE (total) . . . . .</td><td>0.143</td></tr> </table>		RENDER ? . . . . .	NO	DENSITY (kg/m <sup>3</sup> ) . . . . .	1750	RENDER DENSITY . . . . .		DENSITY (mean) . . . . .	1750	SPECIFIC HEAT CAPACITY (J/KgK) . . . . .	790	RENDER SPECIFIC HEAT CAPACITY . . . . .		SPECIFIC HEAT CAPACITY (mean) . . . . .	790	THICKNESS (m) . . . . .	0.1	RENDER THICKNESS . . . . .		THICKNESS (total) . . . . .	0.1	CONDUCTIVITY (W/mK) . . . . .	0.7	RESISTANCE (m <sup>2</sup> K/W) . . . . .	0.143	RENDER RESISTANCE . . . . .		RESISTANCE (total) . . . . .	0.143
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<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;">           CAVITY ? (75mm) VENTILATED CAVITY? NO            CAVITY RESISTANCE: 0.180            HFS No.         </div> <div style="width: 45%;">           INSULATION? YES (40mm Jablite)            INSULATION RESISTANCE: 1.080 (Rigid board)            HFS CALIBRATION FACTOR:         </div> </div>																													

**Table 6.3.1:**  
*Properties of wall construction - Site 1 - Wall type C*





**Fig. 6.3.1:**  
*Cross section through the wall construction - Site 1 - Wall type C*



**Fig. 6.3.2:**  
*Position of HFSs on the wall surface - Site 1 - Wall type C*

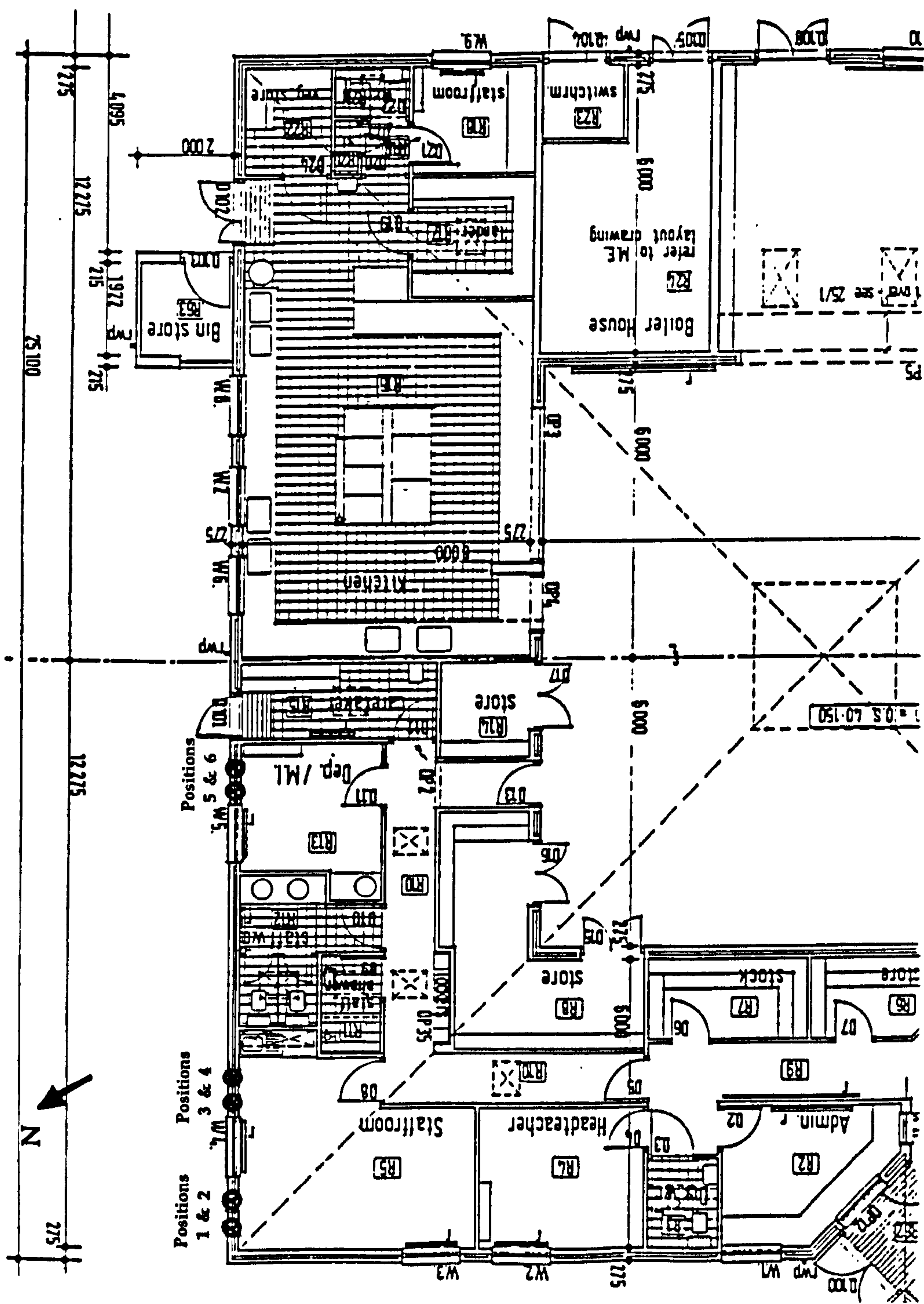



Fig. 6.3.3:

Location of HFSs on the wall surface - Plan view - Site 1 - Wall type C



**SITE 1**

**DATA ANALYSIS**

	P1	P2	P3	P4	P5	P6
M1	1	2				
M2	3	1	2			
M3		3	1	2		
M4			3	1	2	
M5				3	1	
M6						1

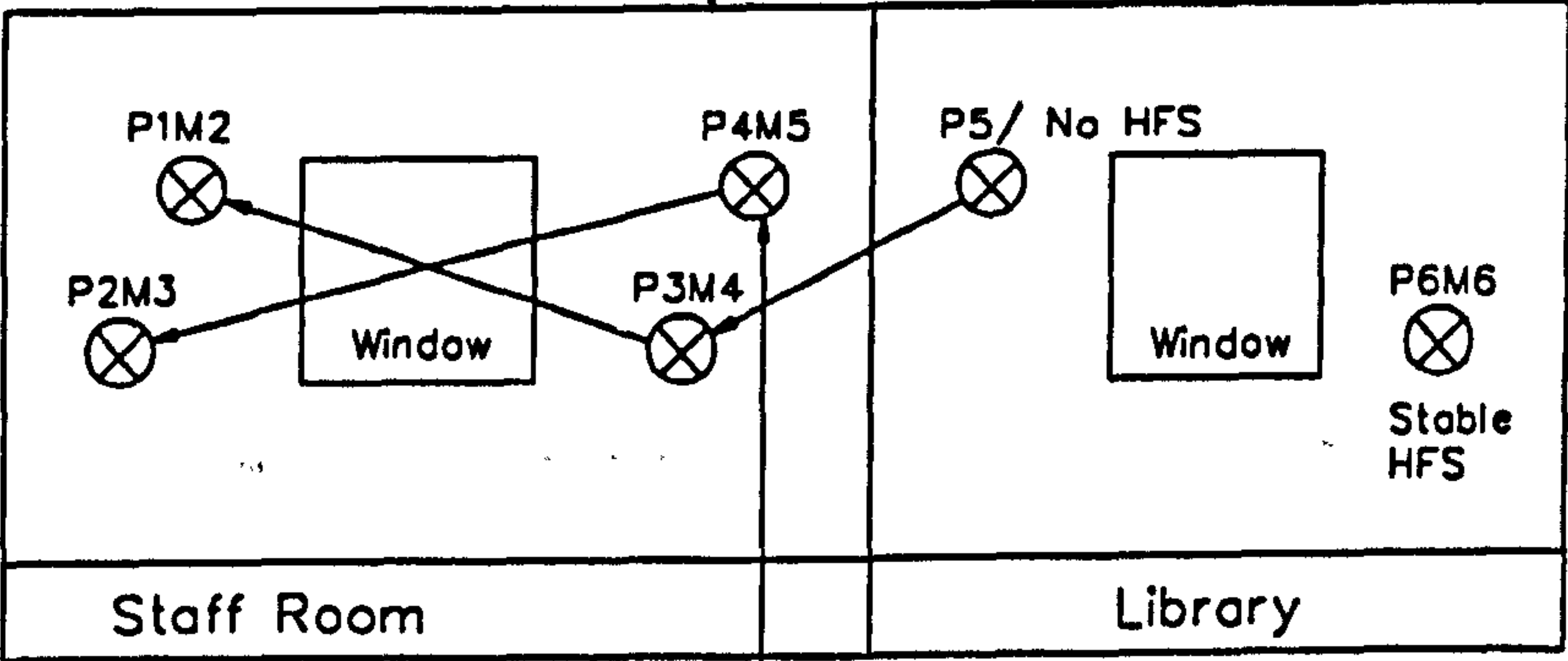
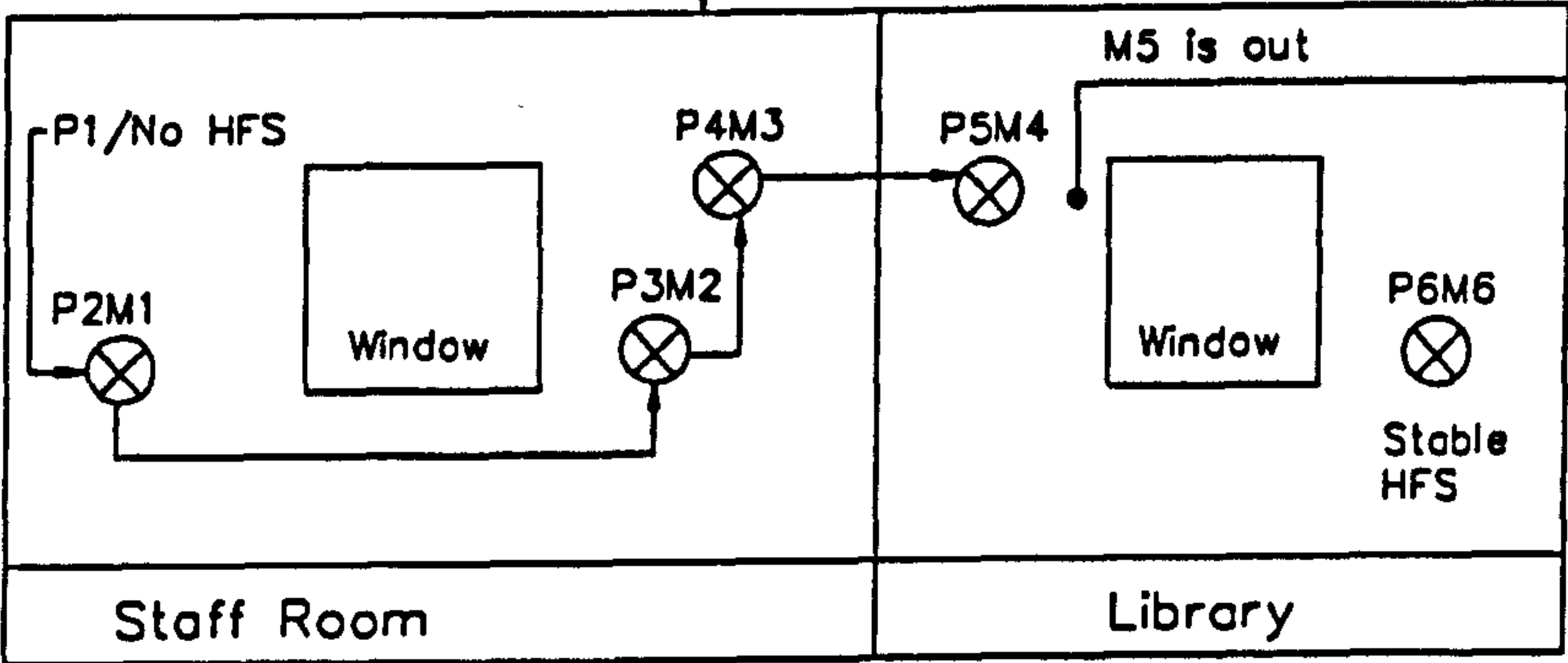
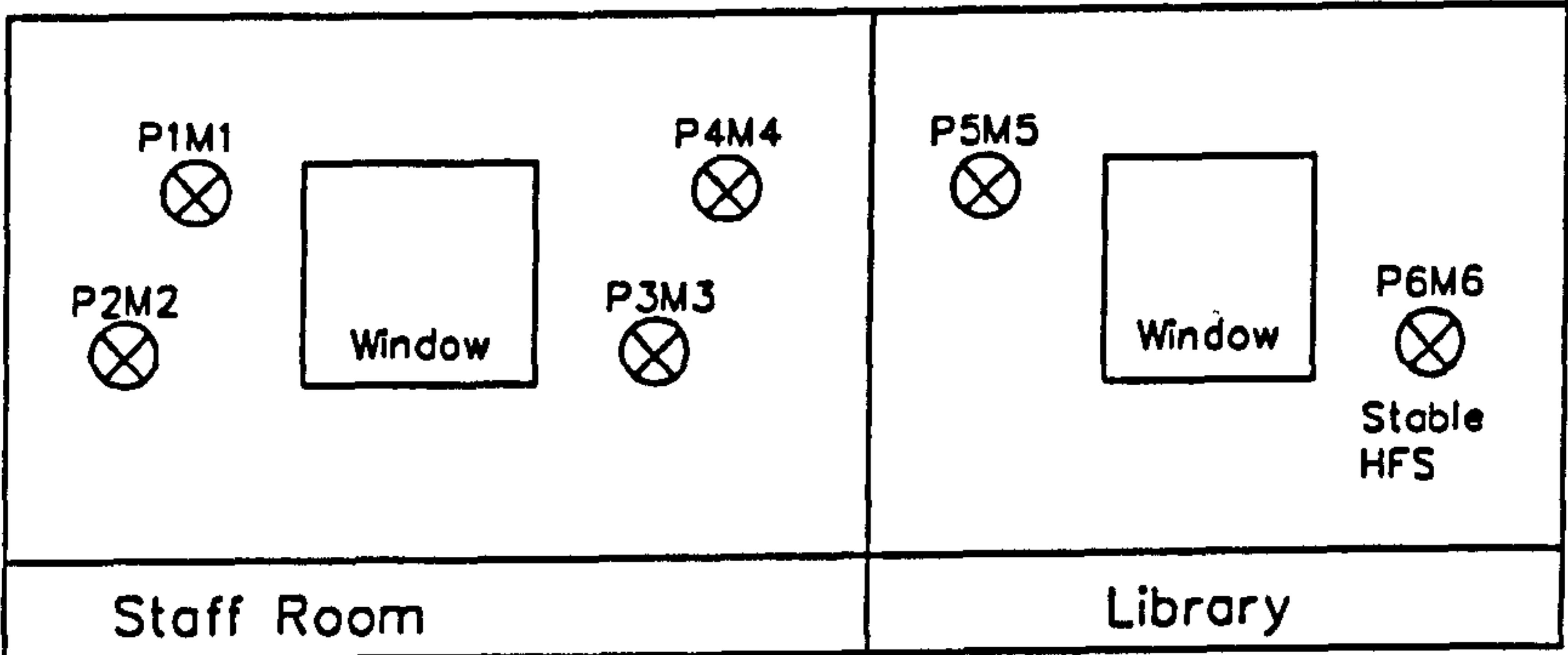



Fig. 6.3.4:  
HFSs rotation pattern - Site 1 - Wall type C



Position	Sensor No:	Averaging Method $\Lambda$ Value			Anderson Method $\Lambda$ Value			Averaging Corrected Value
		Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Anderson Corrected Value
1	63	0.8776	0.8680	0.9114	0.8681	0.8586	0.9015	1.0110
2	68	0.6388	0.6350	0.6668	0.6300	0.6262	0.6575	1.0141
3	65	0.6164	0.6400	0.6720	0.6905	0.6329	0.6645	1.0112
4	66	0.6086	0.5940	0.6237	0.6026	0.5881	0.6175	1.0100
5	69	0.8594	0.8648	0.9080	0.8274	0.8326	0.8742	1.0387
6	64	0.6113	0.6091	0.6396	0.5815	0.5794	0.6084	1.0513
2	63	0.5927	0.5862	0.6155	0.5911	0.5846	0.6138	1.0026
3	68	0.6102	0.6065	0.6368	0.6103	0.6066	0.6369	0.9998
4	65	0.6017	0.6248	0.6560	0.6018	0.6249	0.6561	0.9997
5	66	0.7264	0.7090	0.7444	0.7447	0.7269	0.7632	0.9754
6	64	0.5227	0.5208	0.5468	0.5455	0.5435	0.5707	0.9582
1	68	0.9525	0.9468	0.9941	0.9166	0.9111	0.9567	1.0393
2	65	0.6602	0.6856	0.7199	0.6227	0.6466	0.6789	1.0602
3	66	0.6176	0.6028	0.6329	0.6040	0.5895	0.6190	1.0225
4	69	0.6168	0.6207	0.6517	0.5848	0.5885	0.6179	1.0547
6	64	0.5878	0.5857	0.6150	0.5551	0.5531	0.5808	1.0589
MEAN VALUE ➡								1.0192

Table 6.3.2:  
 Results - Site 1 - Wall type C

SENSOR SERIAL NO:	POSITION MAT	COLD P1 BRIDGE	P2	P3	P4	COLD P5 BRIDGE	P6
63	M1	0.9015	0.6138				
68	M2	0.9567	0.6575	0.6369			
65	M3		0.6789	0.6645	0.6561		
66	M4			0.6190	0.6175	0.7632	
69	M5				0.6179	0.8742	
64	M6						0.6084 0.5707 0.5808
MEAN 		0.9291	0.6501	0.6401	0.6305	0.8187	0.5866

**Table 6.3.3:**

*Results - Matrix format - Site 1 - Wall type C*



START DATE: 11/01/89
END DATE: 25/01/89
DURATION: 14 DAYS
LOCATION:
CRAMLINGTON - BURNSIDE FIRST SCHOOL
RECORDING INSTRUMENT / No.
B / 65
WALL CONSTRUCTION:
OUTER LEAF: STOURBRIDGE BRICK
INSULATION: YES - JABLITE (40mm)
INNER LEAF: FORTICRETE BLOCK
FILE NAME: C28FSRTR.001
COMMENTS:
CRAMLINGTON - BURNSIDE FIRST SCHOOL 5 HFS'S WERE USED. THIS IS THE DATA FROM THE TOP RIGHT HFS IN THE STAFF ROOM. 2nd SERIES.
BUILDING SCIENCE SECTION
SCHOOL OF ARCHITECTURE
NEWCASTLE UNIVERSITY

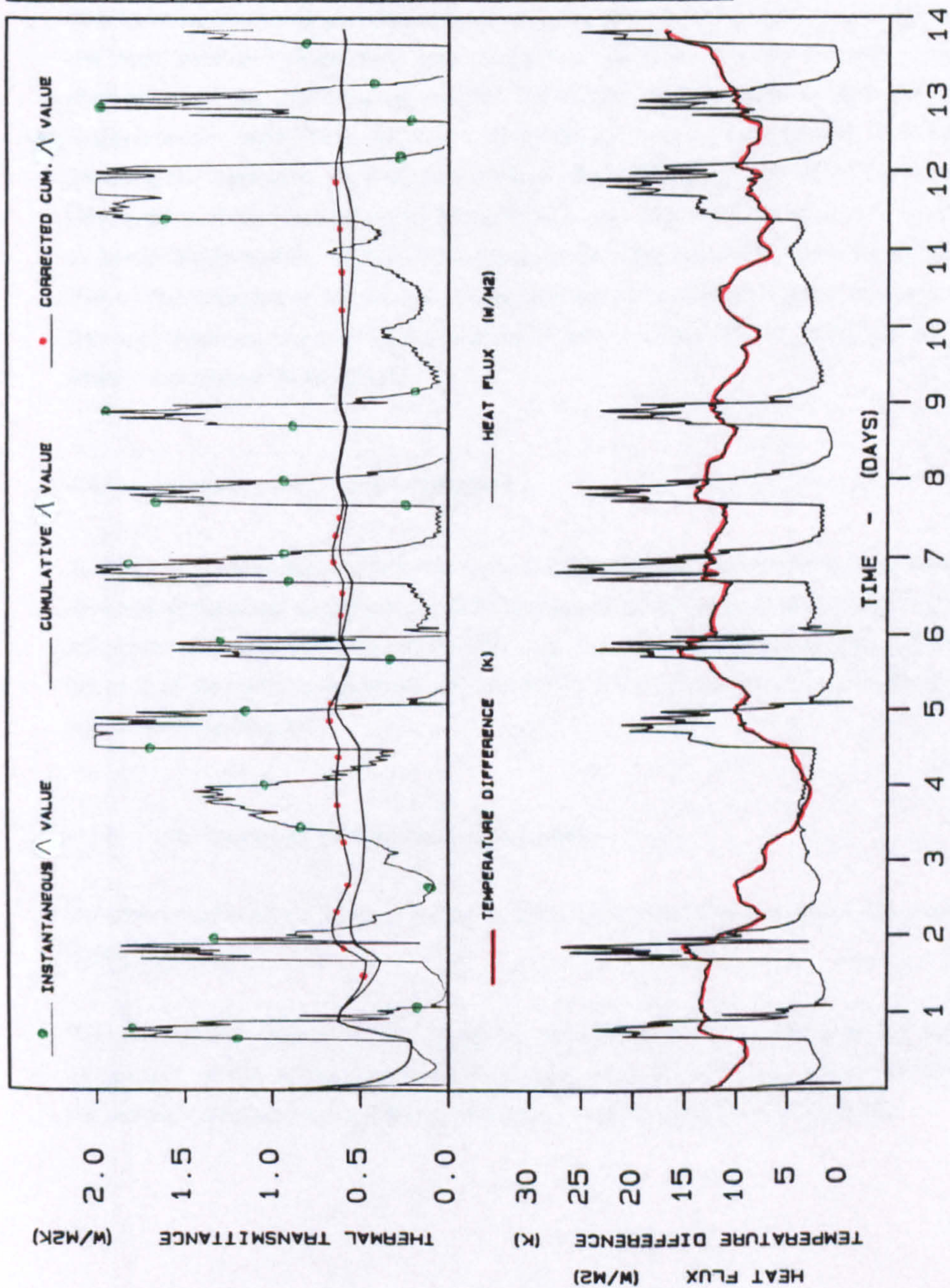


Fig. 6.3.5:

Indicative sample of temperature difference, heat flux, instantaneous  $\Lambda$  value, cumulative (Averaging)  $\Lambda$  value, corrected (Anderson)  $\Lambda$  value - Site 1 - Wall type C



**6.4.0 The measurement (Site 2)**

Four measurements were undertaken at Site 2 which consisted of 2 classrooms at the ground floor of a new extension at the Wensleydale Middle School - Blyth. The wall was of brick/partially filled cavity/block/plaster construction. The 60mm wall cavity was partially insulated with a 30mm Dow - Wallmate CW rigid board (lightweight closed-cell material made from expanded polystyrene of 0.028 W/mK conductivity). Table 6.4.1 gives the properties of the wall construction and a section of the wall is illustrated in Fig. 6.4.1.

The location of the measurement positions was determined by the availability of space on the wall surface (which was very limited in this case due to the fact that the major proportion of the north facing wall of the classrooms consisted of fenestration) and the requirement to place the sensors on a thermally uniform area of the wall. This was achieved by using the infrared camera so that thermal abnormalities on the wall could be established. One area of nearly uniform temperature field was identified as well as one area of gross defect in the insulation system. The mortar joints were not visible with the infrared camera, due to the presence of the insulation layer in the cavity airspace forming the major part of the total resistance of the wall structure. It was not possible to define clearly where the sensor was placed at the block.

**6.4.1 Description of the measurement**

A series of 2 measurement periods was undertaken. The measurement positions were at 2 separate classrooms in the same north facing wall (Fig. 6.4.2). One HFSs was placed in the left classroom, at Position 1 and one HFS was placed in the right classroom at Position 2 (Fig. 6.4.3). Both positions were measured by 2 HFSs. The duration of each monitoring period was approximately 16 days.

**6.4.2 The measured performance of the wall**

The measured wall performance is detailed in Table 6.4.2 and presented in a matrix form in Table 6.4.3.

The corrections applied to the measured values were; firstly, the term for the "relative" calibration of the HFSs and secondly a correction of +4.8%, to allow for the heat flux distortion, calculated using Trethowen's correlation (chapter 5 - section 5.1.2).



Fig. 6.4.4 shows the temperature difference, the heat flux through the wall, the instantaneous  $\Lambda$  value, the Averaging and the Anderson cumulative  $\Lambda$  values for a representative measurement point (1st monitoring period - Position 2 - Site 2).

The conductance values derived using the Averaging and the Anderson methods were found to be close together with the difference between the two values not exceeding 4.8% for any single measurement. The Averaging method gave slightly lower estimates on average, but this was less than 3.0% and the Anderson values are taken as the appropriate measure of the wall transmittance.

A gross defect was identified for Position 1 and a nearly uniform temperature field for Position 2.

Focusing on Position 2 it is evident that different sensors record similar values, the successive measurements taken indicate that the  $\Lambda$  value was reasonably stable with time. The mean value for Position 2 is 0.5623 with less than a 5% variation between the two values.

The cold bridge at Position 1 gave consistently higher values with a mean  $\Lambda$  value of 0.7953 and a variation of less than 9% between the two values (Table 6.4.3). Boroscopic examination revealed a possible cause for the discrepancy. The rigid insulation board was detached from the inner leaf at the point where the measurement took place. Plate 6.4.1 indicates the detachment of the insulation board. Plate 6.4.2 illustrates the manufacturers recommended installation of rigid board insulation (Dow - 1987).

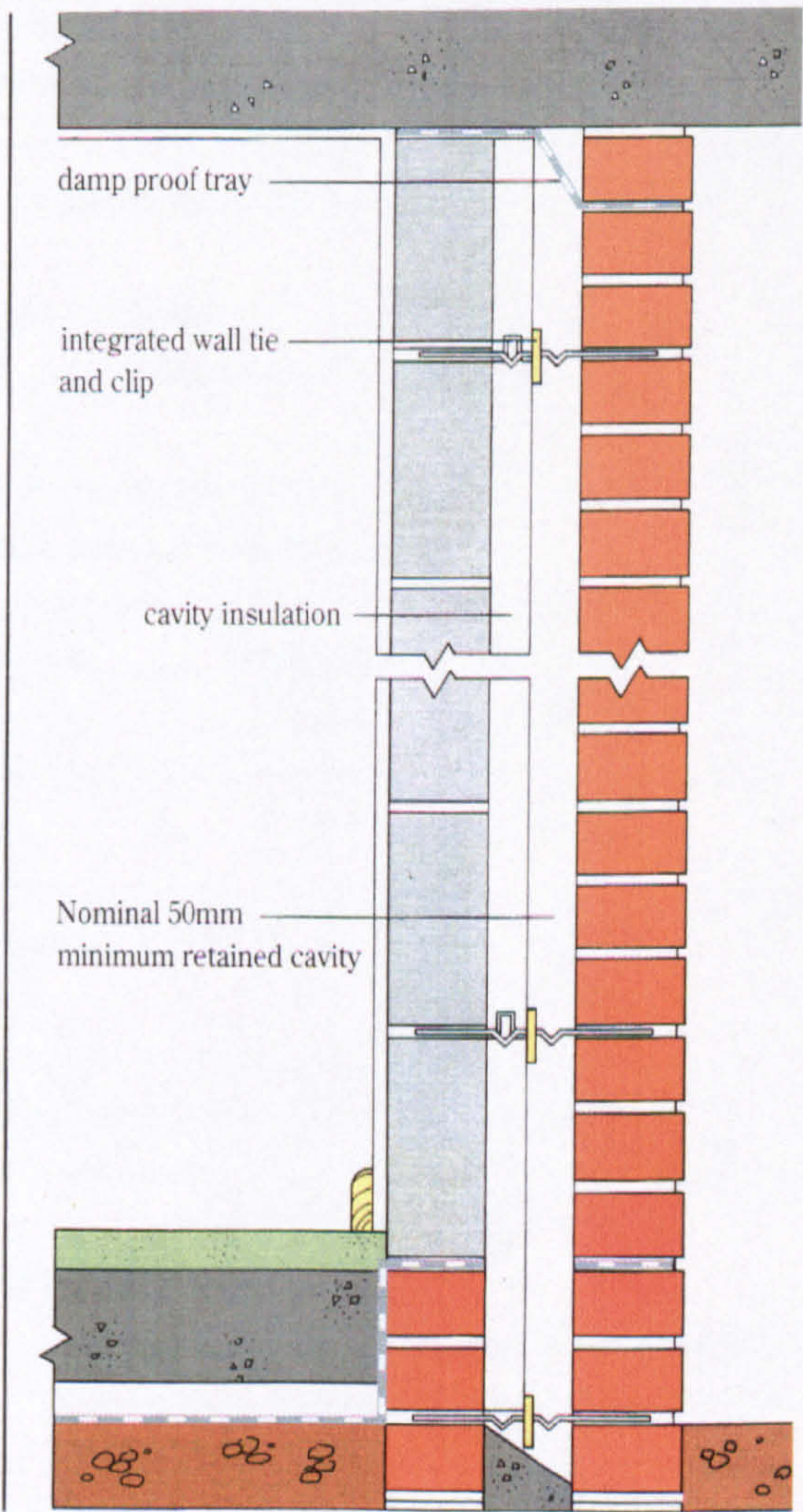
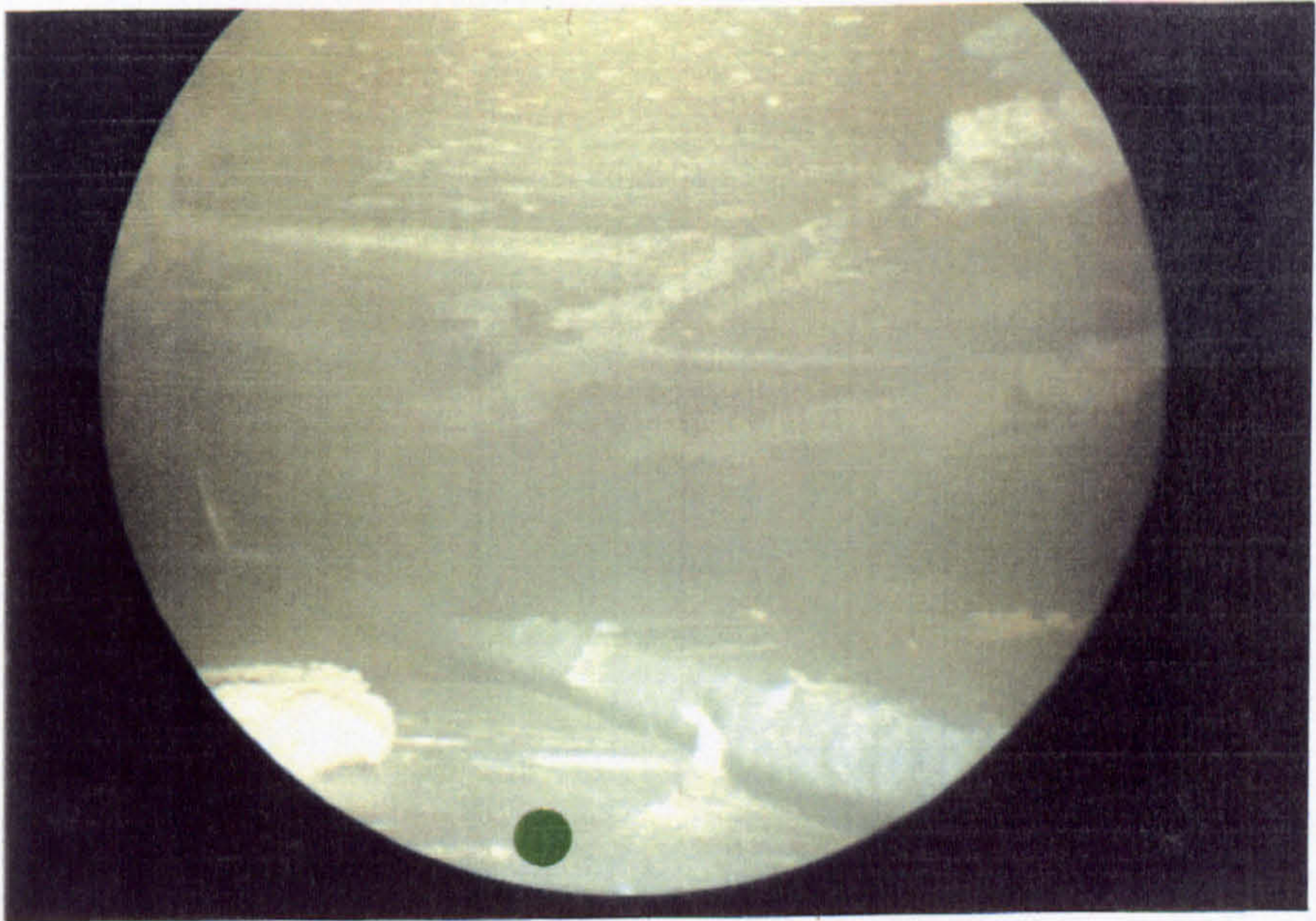
The effect of the cold bridge at Position 1 is to increase the transmittance of the wall at this point from 0.5623 to 0.7953, an increase of 41%. The  $\Lambda$  value of this particular type of wall construction without insulation included in the cavity airspace is 1.36 W/m<sup>2</sup>K. It is clear that the sensor is recording high because the insulation board is not firmly positioned in contact with the wall which leads to convection currents being set up in the gap behind the insulation. In such a case the sensor will measure the effect which presumably varies depending on the size of the gap behind the insulation and is likely to give any value between 0.56 and 1.36 W/m<sup>2</sup>K.

Examination with the boroscope provided the evidence that recommended building practice is not followed and a relatively small defect could lead to a large change in the  $\Lambda$  value at this particular point. The importance of quality control on-site at the time of building is therefore paramount.

**BUILDING PRACTICE**  
**FOR**  
**INSULATION MATERIAL (RIGID BOARDS)**  
**IN**  
**THE CAVITY AIRSPACE**

**The upper Plate (Plate 6.4.1) [where the detached (from the inner leaf) rigid insulation board can clearly be seen at the lower part of the Plate/green dot] indicates the departure from recommended building practice which is illustrated in the lower Plate (Plate 6.4.2) [Manufacturers trade literature/Dow - 1987].**





Upper Plate 6.4.1

Lower Plate 6.4.2



6.4.3    Determination of the theoretical performance of the wall

The following models were used to calculate the theoretical performance of the wall:

- (1) the CIBSE 1D model
- (2) finite element model

**CIBSE 1D model:**

The  $\Lambda$  value was calculated according to the CIBSE Guide which assumes homogeneous construction by taking into account the thermophysical properties of each separate layer comprising the wall. The best estimate of the  $\Lambda$  value was 0.56 W/m<sup>2</sup>K using the values in Table 6.4.4.

**Finite element model:**

In order to achieve a better approximation, an additional set of calculations was carried out i.e. a 3D finite element model was applied. Two estimates are presented for the  $\Lambda$  value of this wall, a block average value of 0.57 and a block centre value of 0.55. The conditions applied are given in Table 6.4.4.

In the modelling process the wall surface resistances (m<sup>2</sup>K/W) were taken as:

Internal	Cavity	External
0.123	0.09	0.03

<b>Ident: Site 2 - Wall Type C</b>		
<b>Material</b>	<b>Thickness (mm)</b>	<b>Resistance (m<sup>2</sup>K/W)</b>
Brick	100	0.133
Cavity	60	
Insulation	30	1.070
Block	100	0.313
Plaster	13	0.110
Mortar joint	100	0.125
<b>Table 6.4.4:</b> <i>Construction details used for thermal modelling - Site 2 - Wall type C</i>		



6.4.4 Comparison between the measured and theoretical transmittance values

The values obtained are shown in Table 6.4.5.

	FE Model ling	CIBSE Guide 1D	Measured values
Block average	0.57	X	0.56
Block centre	0.55	0.56	
<b>Table 6.4.5:</b> <i>FE, CIBSE and measured transmittance (W/m<sup>2</sup>K) values for a brick/partially filled cavity/block/plaster wall - Site 2 - Wall type C</i>			

Table 6.4.5 indicates the consistency of the values for the two models used. The value of 0.56 resulting from the CIBSE 1D model is very nearly the same as the FE block centre value of 0.55 and the FE block average value of 0.57. The measured value of 0.56 also compares very favourably with the above values.

Given the experimental errors and the uncertainty in calculating the theoretical performance due to possible differences in material properties and dimensions between the actual and theoretical walls, there is a suprisingly good agreement, between the measured and all the values resulting from the application of the theoretical models.

From the measured data (only one measurement position), the best estimate of the average wall performance is 0.56.

Finally, while the evidence is not conclusive due to the very small sample it is reasonable to assume that this wall behaves according to the design specifications. From this study the best estimate for the average measured wall performance is 0.56 which is in very close agreement with the theoretical values.

**SITE 2**

**WALL DETAILS**

**PHYSICAL DESCRIPTION**

**OF**

**THE WALL**

**AND**

**LOCATION OF HFSs**



<b>ID:</b> Wall type C Site 2	<b>PROPERTIES OF WALL CONSTRUCTION</b>																												
<b>SITE:</b> BLYTH - WENSLEYDALE MIDDLE SCHOOL (CLASSROOMS)																													
<b>SITE No.:</b>	<b>SERIES OF MEASUREMENT:</b>																												
<b>DATE:</b> WINTER 89																													
<b>CONSTRUCTION YEAR:</b>	<b>FILENAME:</b>																												
<b>INNER LEAF:</b> ARMSTRONG PELLITE STANDARD CONCRETE BLOCK (SOLID)																													
<table style="width: 100%; border: none;"> <tr><td style="width: 80%;">PLASTER .....</td><td style="width: 20%;">YES</td></tr> <tr><td>DENSITY (Kg/m<sup>3</sup>) .....</td><td>1350</td></tr> <tr><td>PLASTER DENSITY .....</td><td>700</td></tr> <tr><td>DENSITY (mean) .....</td><td>1275</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) .....</td><td>1000</td></tr> <tr><td>PLASTER SPECIFIC HEAT CAPACITY .....</td><td></td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) .....</td><td>1000</td></tr> <tr><td>THICKNESS (m) .....</td><td>0.1</td></tr> <tr><td>PLASTER THICKNESS .....</td><td>0.013</td></tr> <tr><td>THICKNESS (total) .....</td><td>0.113</td></tr> <tr><td>CONDUCTIVITY (W/mK) .....</td><td>0.32</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) .....</td><td>0.313</td></tr> <tr><td>PLASTER RESISTANCE .....</td><td>0.110</td></tr> <tr><td>RESISTANCE (total) .....</td><td>0.423</td></tr> </table>		PLASTER .....	YES	DENSITY (Kg/m <sup>3</sup> ) .....	1350	PLASTER DENSITY .....	700	DENSITY (mean) .....	1275	SPECIFIC HEAT CAPACITY (J/KgK) .....	1000	PLASTER SPECIFIC HEAT CAPACITY .....		SPECIFIC HEAT CAPACITY (mean) .....	1000	THICKNESS (m) .....	0.1	PLASTER THICKNESS .....	0.013	THICKNESS (total) .....	0.113	CONDUCTIVITY (W/mK) .....	0.32	RESISTANCE (m <sup>2</sup> K/W) .....	0.313	PLASTER RESISTANCE .....	0.110	RESISTANCE (total) .....	0.423
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<b>OUTER LEAF :</b> WESTBRICK ELDON RANGE VICTORIA BUFF FACING BRICK																													
<table style="width: 100%; border: none;"> <tr><td style="width: 80%;">RENDER ? .....</td><td style="width: 20%;">NO</td></tr> <tr><td>DENSITY (kg/m<sup>3</sup>) .....</td><td>1750</td></tr> <tr><td>RENDER DENSITY .....</td><td></td></tr> <tr><td>DENSITY (mean) .....</td><td>1750</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) .....</td><td>790</td></tr> <tr><td>RENDER SPECIFIC HEAT CAPACITY .....</td><td></td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) .....</td><td>790</td></tr> <tr><td>THICKNESS (m) .....</td><td>0.1</td></tr> <tr><td>RENDER THICKNESS .....</td><td></td></tr> <tr><td>THICKNESS (total) .....</td><td>0.1</td></tr> <tr><td>CONDUCTIVITY (W/mK) .....</td><td>0.75</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) .....</td><td>0.133</td></tr> <tr><td>RENDER RESISTANCE .....</td><td></td></tr> <tr><td>RESISTANCE (total) .....</td><td>0.133</td></tr> </table>		RENDER ? .....	NO	DENSITY (kg/m <sup>3</sup> ) .....	1750	RENDER DENSITY .....		DENSITY (mean) .....	1750	SPECIFIC HEAT CAPACITY (J/KgK) .....	790	RENDER SPECIFIC HEAT CAPACITY .....		SPECIFIC HEAT CAPACITY (mean) .....	790	THICKNESS (m) .....	0.1	RENDER THICKNESS .....		THICKNESS (total) .....	0.1	CONDUCTIVITY (W/mK) .....	0.75	RESISTANCE (m <sup>2</sup> K/W) .....	0.133	RENDER RESISTANCE .....		RESISTANCE (total) .....	0.133
RENDER ? .....	NO																												
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<table style="width: 100%; border: none;"> <tr> <td style="width: 50%;">CAVITY ? (60mm) VENTILATED CAVITY ? NO</td> <td style="width: 50%;">INSULATION ? YES</td> </tr> <tr> <td>CAVITY RESISTANCE: 0.180</td> <td>INSULATION RESISTANCE: 1.070</td> </tr> <tr> <td>HFS No.</td> <td>HFS CALIBRATION FACTOR:</td> </tr> </table>		CAVITY ? (60mm) VENTILATED CAVITY ? NO	INSULATION ? YES	CAVITY RESISTANCE: 0.180	INSULATION RESISTANCE: 1.070	HFS No.	HFS CALIBRATION FACTOR:																						
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HFS No.	HFS CALIBRATION FACTOR:																												

(30mm PARTIALLY)  
 (FILLED CAVITY )  
 (WITH WALLMATE )  
 (CW-DOW )

**Table 6.4.1:**  
*Properties of wall construction - Site 2 - Wall type C*

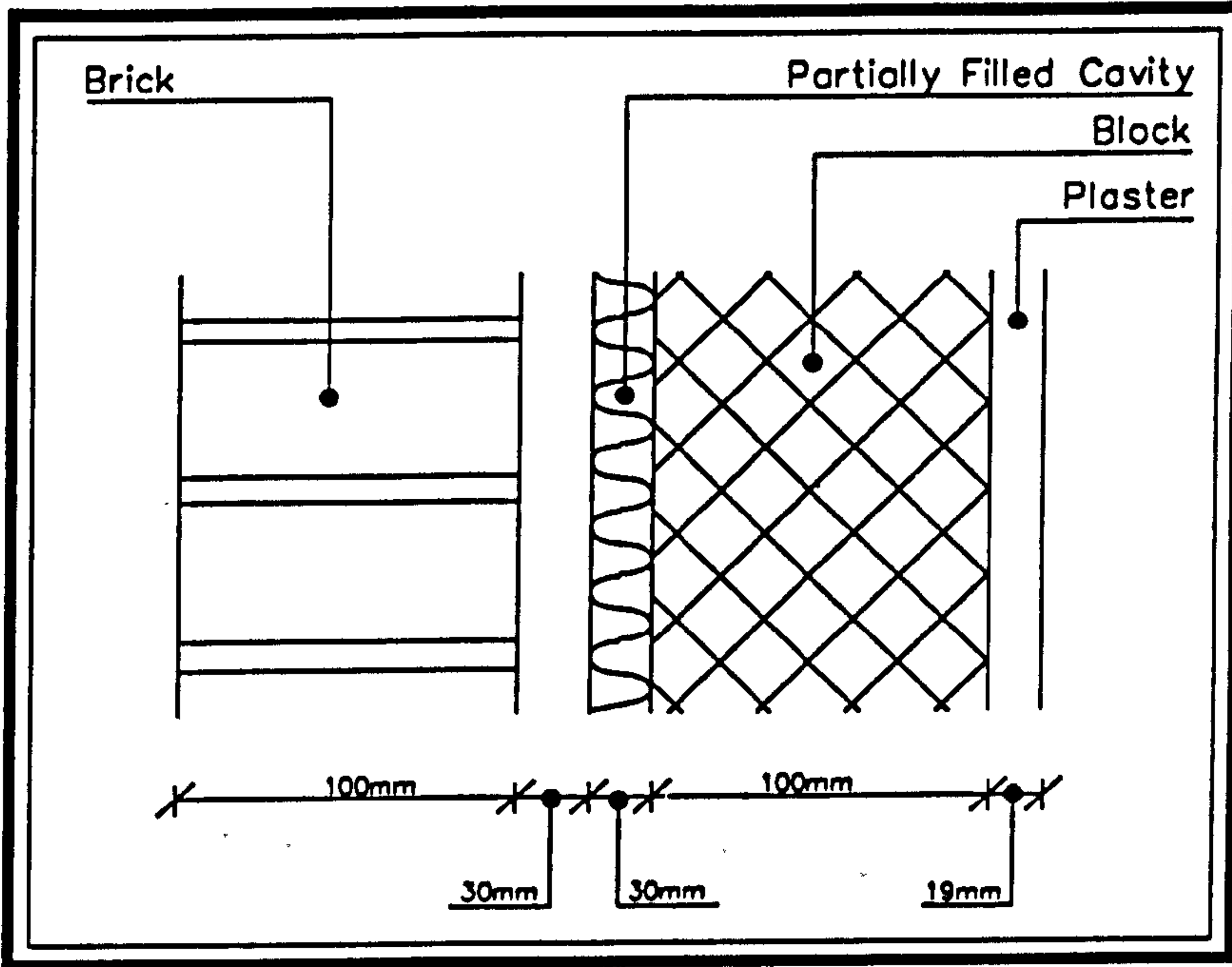


Fig. 6.4.1:  
Cross section through the wall construction - Site 2 - Wall type C

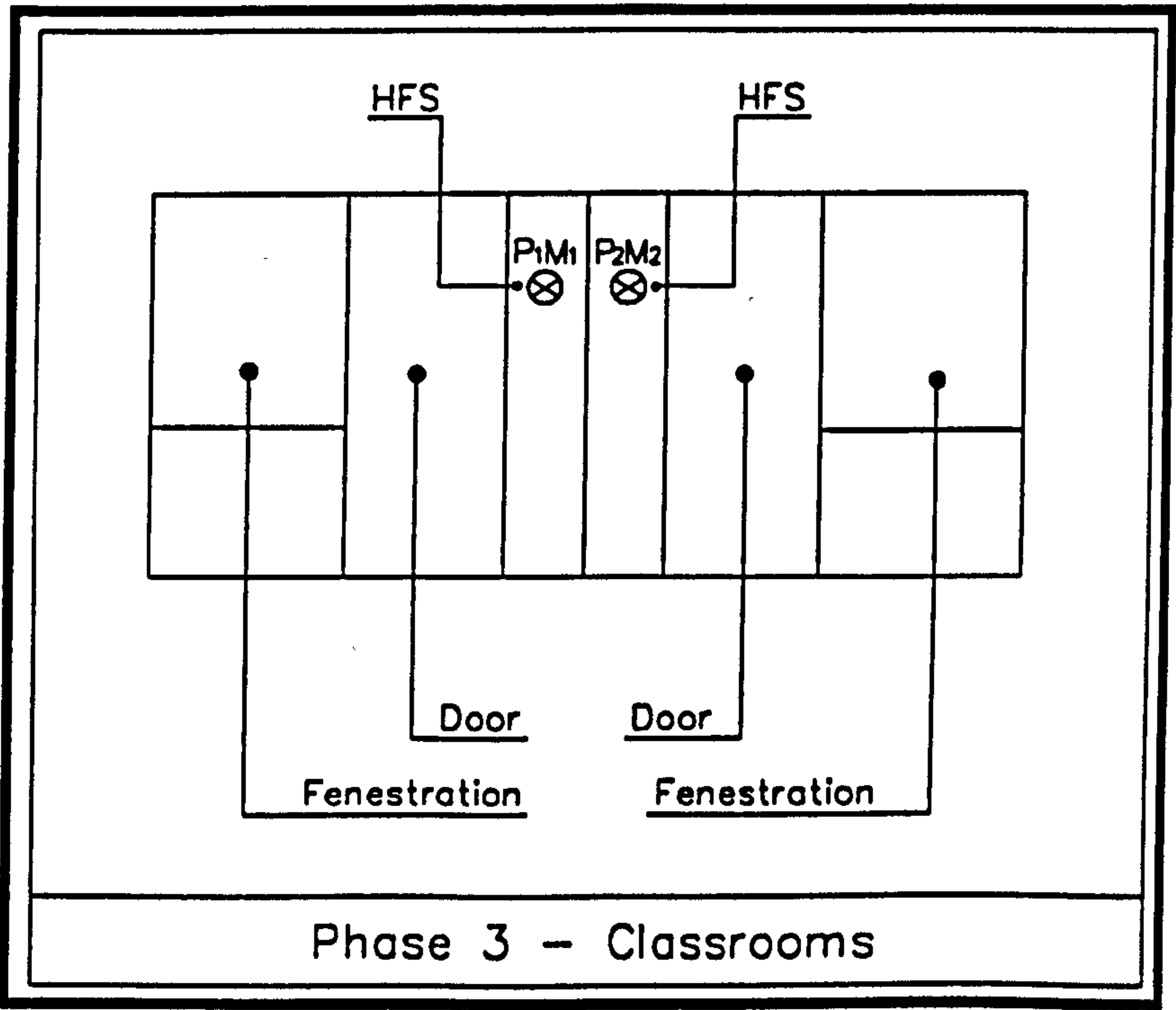


Fig. 6.4.2:  
Position of HFSs on the wall surface - Site 2 - Wall type C



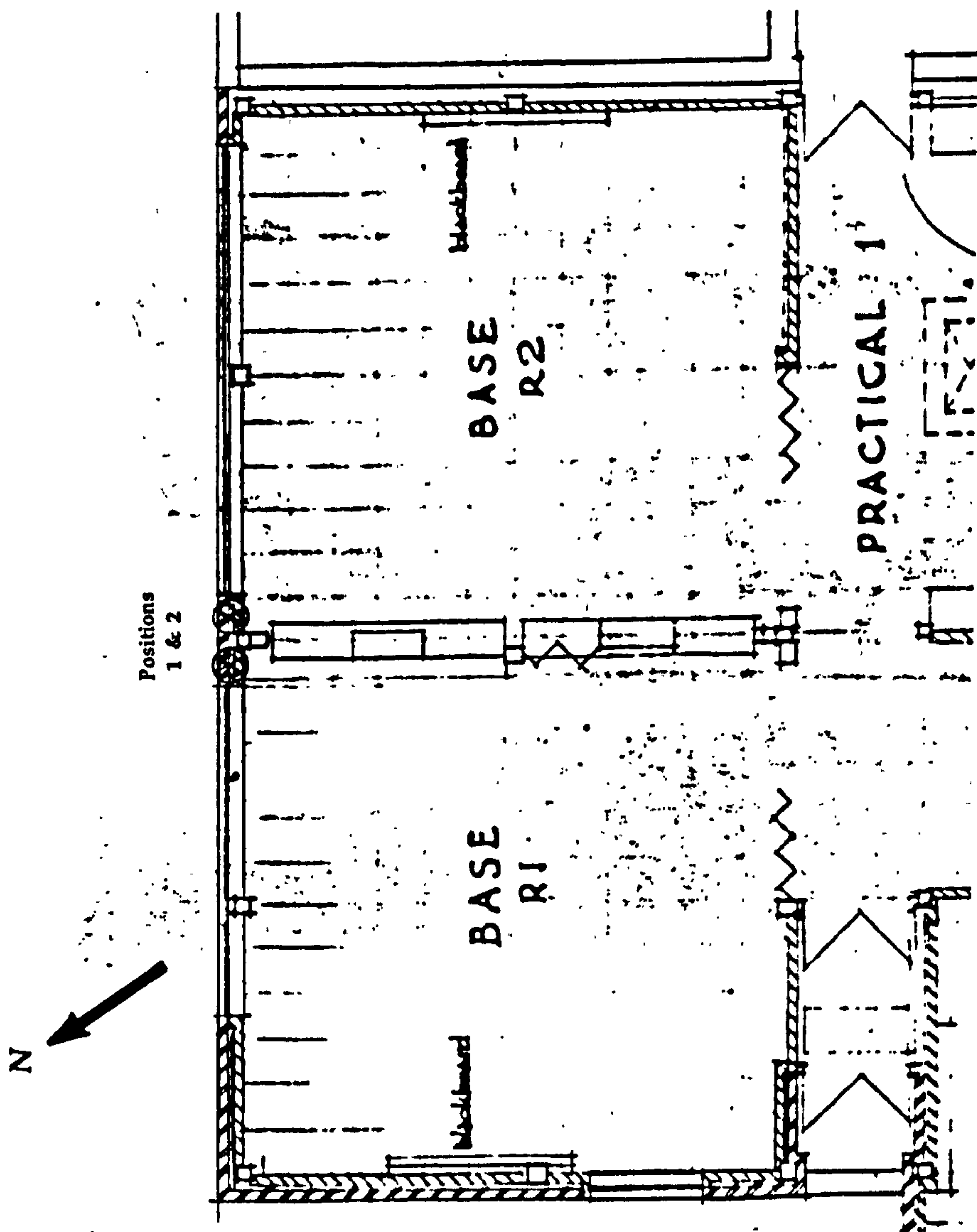


Fig. 6.4.3:

Location of HFSs on the wall surface - Plan view - Site 2 - Wall type C

SITE 2

DATA ANALYSIS



Position	Sensor No:	Averaging Method $\Lambda$ Value			Anderson Method $\Lambda$ Value			Averaging Corrected Value
		Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Anderson Corrected Value
1	68	0.7265	0.7221	0.7568	0.7283	0.7239	0.7586	0.9976
2	63	0.5233	0.5175	0.5423	0.5291	0.5233	0.5484	0.9890
2	68	0.5265	0.5233	0.5484	0.5530	0.5497	0.5761	0.9519
1	63	0.7864	0.7777	0.8150	0.8027	0.7939	0.8320	0.9796
MEAN VALUE ➡								0.9795

Table 6.4.2:  
 Results - Site 2 - Wall type C


SENSOR SERIAL NO:	POSITION MAT	COLD P1 BRIDGE	P2	P3	P4	P5	P6
68	M1	0.7586	0.5761				
63	M2	0.8320	0.5484				
	M3						
	M4						
	M5						
	M6						
MEAN		0.7953	0.5623				

Table 6.4.3:  
Results - Matrix format - Site 2 - Wall type C



START DATE: 20/02/89
END DATE: 06/03/89
DURATION: 14 DAYS
LOCATION: BLYTH - WENSLEYDALE MIDDLE SCHOOL
RECORDING INSTRUMENT / No.: G / 63
WALL CONSTRUCTION: OUTER LEAF: WESTBRICK BRICK INSULATION: DOW - WALLMATE -30mm INNER LEAF: PELLITE CONCR. BLOCK
FILE NAME: BWSCRR.001
COMMENTS: BLYTH - WENSLEYDALE MIDDLE SCHOOL 2 HFS'S WERE USED. THIS IS THE DATA FROM THE RIGHT CLASSROOM (WITH INSU- LATION, WITH PLASTER). 1st SERIES.
BUILDING SCIENCE SECTION SCHOOL OF ARCHITECTURE NEWCASTLE UNIVERSITY

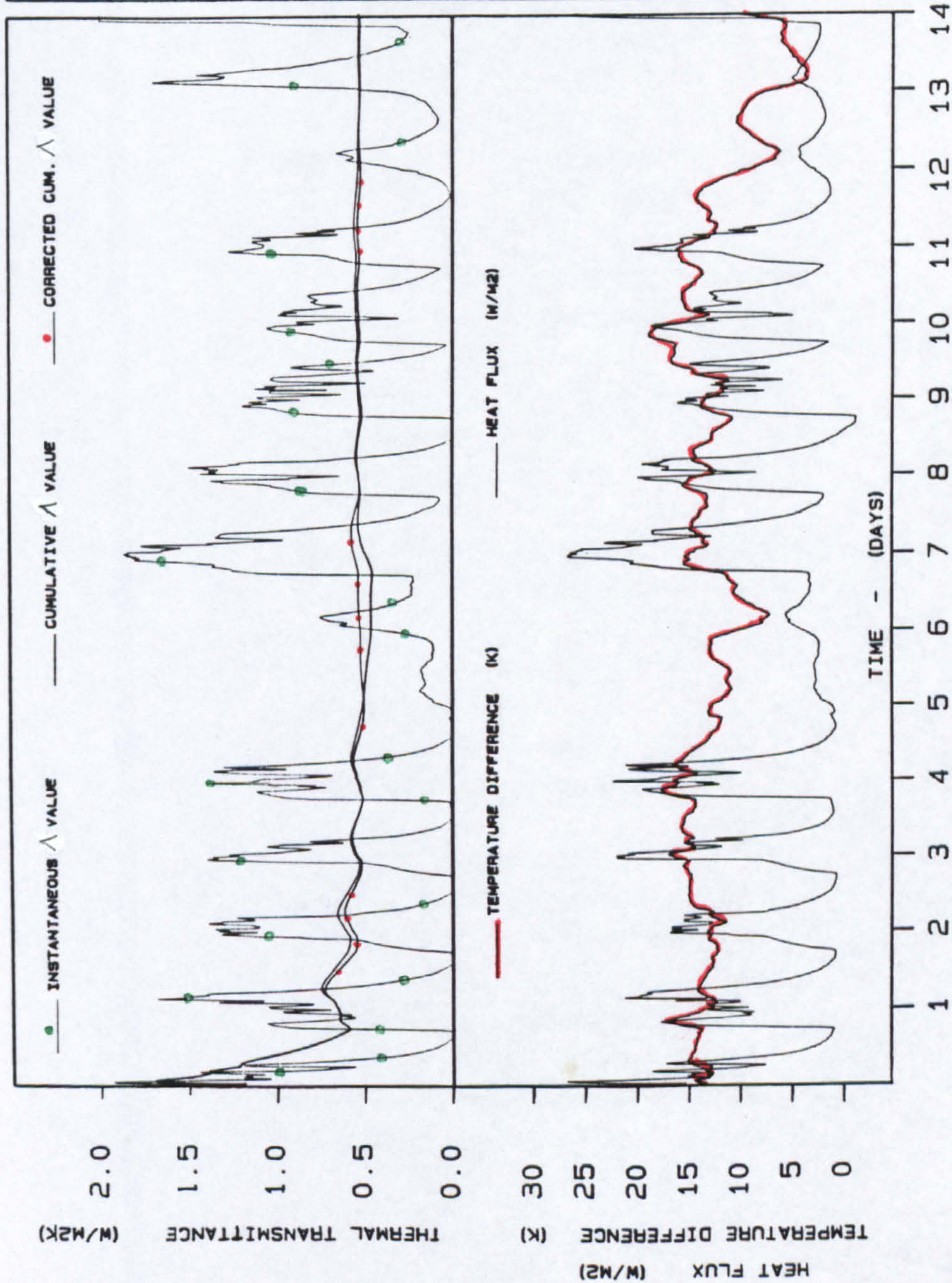


Fig. 6.4.4:

Indicative sample of temperature difference, heat flux, instantaneous  $\Lambda$  value, cumulative (Averaging)  $\Lambda$  value, corrected (Anderson)  $\Lambda$  value - Site 2 - Wall type C



## WALL TYPE D

### CASE STUDIES 5 & 6

**CONSTRUCTION:** BRICK/UNFILLED - FULLY FILLED CAVITY  
(RETROFIT)/BRICK - BLOCK/PLASTER

**LOCATION:** MORPETH - HEPSCOTT PARK  
TILL HOUSE (CASE STUDY 5)  
  
FREEMAN HOSPITAL  
MICROBIOLOGY LAB - (CASE STUDY 6)

**No. OF SITES:** 2

**SITE 1:** MORPETH - HEPSCOTT PARK  
TILL HOUSE

No. of unique measurement points  
(before and after insulation was  
injected in the cavity airspace): 4 (8)  
No. of multiple measurements: None

**SITE 2:** FREEMAN HOSPITAL  
MICROBIOLOGY LAB

No. of unique measurement points  
(before and after insulation was  
injected in the cavity airspace): 3 (6)  
No. of multiple measurements: None



## **6.5/6 An evaluation of the performance of retrofit cavity walls (Wall type D)**

Measurements were carried out in cavity walls before and after insulation was injected in the cavity airspace. The performance of the wall is evaluated by using the same procedure outlined in 6.0.1. Fourteen measurements were undertaken at two Sites, Site 1 and Site 2.

### **6.5.0 The measurement (Site 1)**

Eight measurements were undertaken at Site 1 which was in Hepscott Park - Morpeth. The area comprised of several buildings which were part of an administration complex and old people's housing. The majority of the buildings were of brick/cavity/brick/plaster construction and were used as military hospitals in the First World War. The Site was monitored before and after insulation was injected in the cavity.

Table 6.5.1 gives the properties of the wall construction and a section of the wall (before and after insulation was injected in the cavity airspace) is illustrated in Figs. 6.5.1 and 6.5.2. The location of the measurement positions was determined by the availability of space on the wall surface and the requirement to place the sensors on a thermally uniform area of the wall. This was achieved by using the infrared camera so that thermal abnormalities on the wall could be established and avoided.

The mortar joints were not visible with the infrared camera due to the brickwork having a density of  $1800 \text{ Kg/m}^3$  and a conductivity nearly the same with that of the mortar. It should be noted that the thermographic survey was employed only once and that was before insulation was injected in the cavity.

### **6.5.1 Description of the measurement**

Four HFSs were placed on the wall surface at the positions shown in Fig. 6.5.3 and they were all retained in the same position throughout the 2 monitoring periods. The measurement positions were all in the same north facing wall (Fig. 6.5.4). A series of two measurement periods was undertaken (before and after "Cyproc Walltherm blowing wool" insulation of  $0.041 \text{ W/mK}$  conductivity was injected in the 65mm cavity). Each monitoring period was approximately 16 days.

6.5.2 The measured performance of the wall

The measured wall performance is detailed in Table 6.5.2 before insulation was injected in the cavity and in Table 6.5.3 after insulation was injected in the cavity.

The corrections applied to the measured values were; firstly, the term for the "relative" calibration of the HFSs and secondly a calculated correction of +8.6% for clear cavity and +5% for fully filled cavity, to allow for the heat flow distortion using Trethowen's correlation (chapter 5 - section 5.1.2).

Figs. 6.5.5 and 6.5.6 show the temperature difference, the heat flux through the wall, the instantaneous  $\Lambda$  value, the Averaging and the Anderson cumulative  $\Lambda$  values for a representative measurement point (Position 3 - Site 1) for clear and fully filled cavity respectively.

The conductance values derived using the Averaging and the Anderson methods were found to be close together with the difference between any two values not exceeding 4.4% for any single measurement (Tables 6.5.2 and 6.5.3) and the Anderson values are taken as the appropriate measure of the wall transmittance.

For a clear cavity the best estimate of the average wall performance at the 4 measurement positions (1 to 4) is the mean value of 1.5145 with a 11.5% variation between the upper and lower estimates of the measured wall performance (Table 6.5.4).

Position	$\Lambda$ Value (W/m <sup>2</sup> K) (Before insulation was injected in the cavity airspace)	$\Lambda$ Value (W/m <sup>2</sup> K) (After insulation was injected in the cavity airspace)	Difference between the two values
1	1.4700	0.5000	0.9700
2	1.4543	0.5103	0.9440
3	1.6292	0.5122	1.1170
4	1.5043	0.4766	1.0277
Mean value	1.5145	0.4998	1.0147

**Table 6.5.4:**  
*Transmittance values for a brick/cavity/brick/plaster wall - Site 1 - Wall type D  
(Before and after insulation was injected in the cavity airspace)*



For a fully filled cavity the best estimate of the average wall performance at the 4 measurement positions (1 to 4) is the mean value of 0.4998 with a variation of 7.5% between the upper and lower estimates of the measured wall performance (Table 6.5.4).

6.5.3 Determination of the theoretical performance of the wall

The models used to calculate the theoretical performance of the wall were:

- (1) the CIBSE 1D model
- (2) expected 1D model

CIBSE 1D model:

The  $\Lambda$  value was calculated according to the CIBSE Guide which assumes homogeneous construction by taking into account the thermophysical properties of each separate layer comprising the wall. The best estimate of the  $\Lambda$  value was 1.63 W/m<sup>2</sup>K for clear cavity and 0.51 W/m<sup>2</sup>K for fully filled cavity using the values in Table 6.5.5.

Expected 1D value model:

In order to evaluate the expected performance of the wall after insulation was injected in the cavity airspace, the insulation resistance value of 1.5854 m<sup>2</sup>K/W was added to the measured average performance of 0.66 m<sup>2</sup>K/W for a clear cavity wall resulting to a mean  $\Lambda$  value of 0.45 W/m<sup>2</sup>K.

Ident: Site 1 - Wall Type D		
Material	Thickness (mm)	Resistance (m <sup>2</sup> K/W)
Brick	110	0.155
Cavity	65	
Insulation	(None/fully filled)	1.540
Brick	110	0.155
Plaster	19	0.123
Mortar joint	100	0.125
Table 6.5.5: Construction details used for the CIBSE models - Site 1 - Wall type D		

6.5.4 Comparison between the measured and theoretical transmittance values

The values obtained are shown in Table 6.5.6.

CIBSE Guide			
	1D	Expected 1D	Measured Value
<u>Site 1 (clear cavity)</u>			
Brick average	1.63	X	1.51
<u>Site 1 (Fully filled cavity)</u>			
Brick average	0.51	0.45	0.50
<b>Table 6.5.6:</b> <i>CIBSE and measured transmittance values (W/m<sup>2</sup>K) for a retrofit cavity brick wall - Site 1 - Wall type D</i>			

For this homogeneous construction the measured values compare very favourably with CIBSE 1D values. This in fact is the case for both the clear and fully filled cavities.

Before insulation was injected in the cavity the measured value of 1.51 was slightly lower (<9%) than the CIBSE 1D value of 1.63. After insulation was injected in the cavity the measured value of 0.50 was in very good agreement with the CIBSE 1D value of 0.51.

When the measured unfilled cavity value of 1.51 was adjusted using the CIBSE model for 65 mm of cavity insulation the expected value was 0.45, slightly lower than the measured value of 0.50.

Given the experimental errors and the uncertainty in calculating the theoretical performance due to possible differences in material properties and dimensions between the actual and theoretical walls, the measured values of 1.51 and 0.50 compare very favourably with the theoretical values in both, before and after insulation was injected in the cavity.



The evidence is that this wall behaves according to the design specifications for both cases: before and after insulation was injected in the cavity airspace. From this study the best estimate for the measured average wall performance before insulation was injected in the cavity is 1.51, which is in close agreement with the CIBSE 1D value of 1.63. The best estimate for the measured average wall performance after insulation was injected in the cavity is 0.50, which compares very favourably with the CIBSE 1D value of 0.51.

**SITE 1**

**WALL DETAILS**

**PHYSICAL DESCRIPTION**

**OF**

**THE WALL**

**AND**

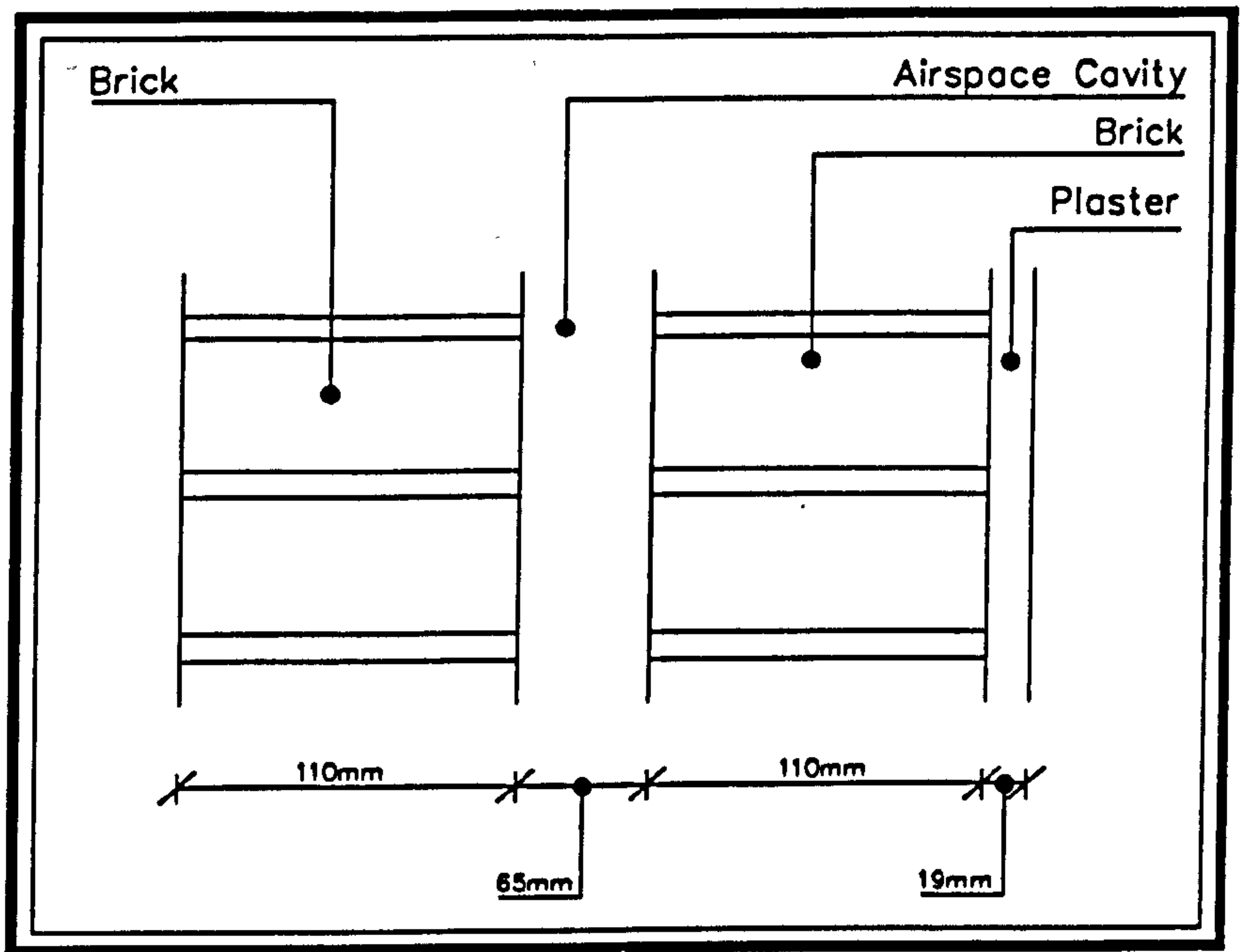
**LOCATION OF HFSs**



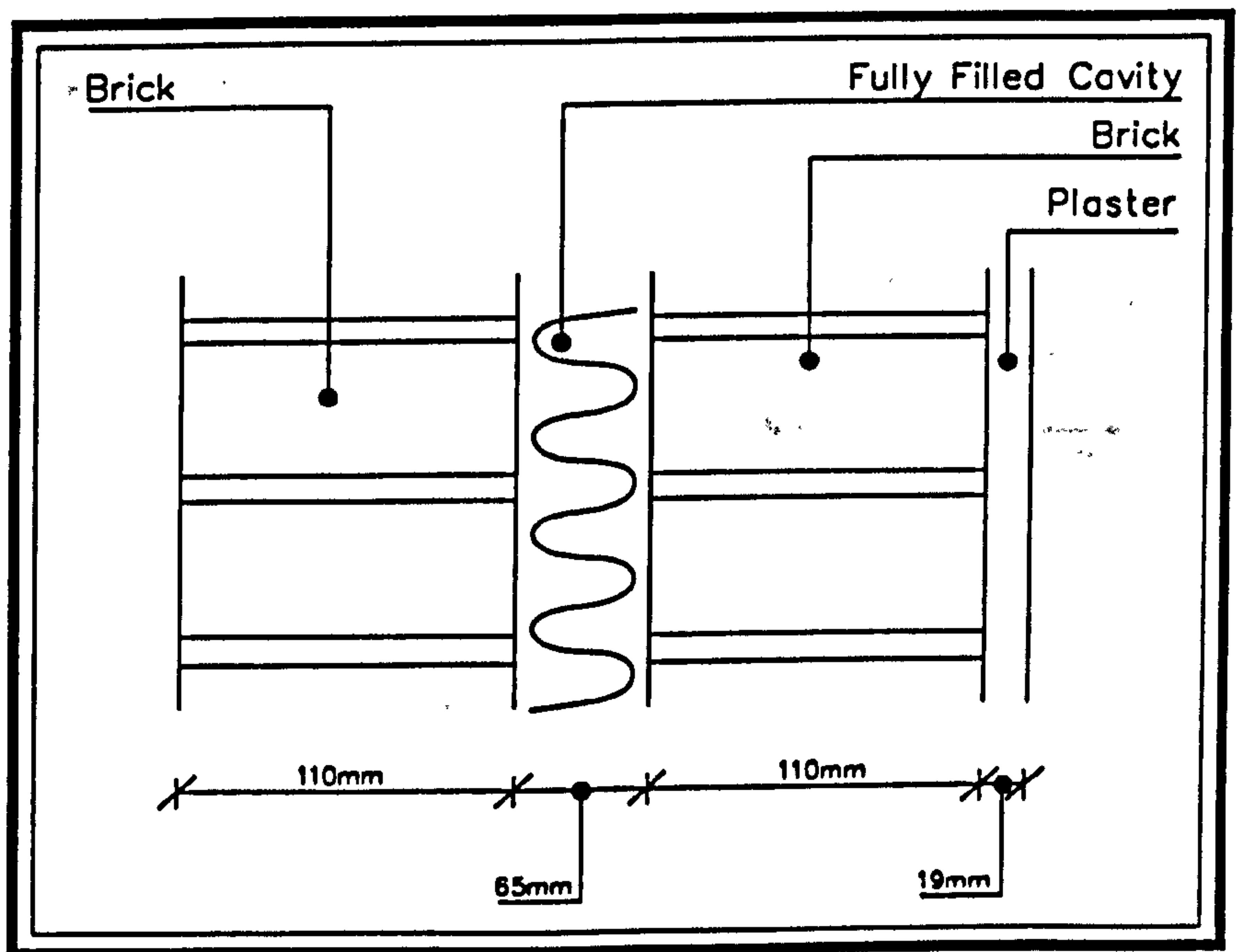
ID : Wall type D Site 1	<b>PROPERTIES OF WALL CONSTRUCTION</b>																												
<p><b>SITE : MORPETH - HEPSCOTT PARK - TILL HOUSE</b></p> <p>             SITE No.:                      SERIES OF MEASUREMENT:                      DATE : NOV 89           </p> <p>             CONSTRUCTION YEAR : 1920-30                      FILENAME:           </p>																													
<p><b>INNER LEAF : COMMON BRICK</b></p> <table style="width: 100%; margin-top: 10px;"> <tr><td>PLASTER .....</td><td>YES</td></tr> <tr><td>DENSITY (Kg/m<sup>3</sup>) .....</td><td>1800</td></tr> <tr><td>PLASTER DENSITY .....</td><td>1000</td></tr> <tr><td>DENSITY (mean) .....</td><td>1680</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) .....</td><td>790</td></tr> <tr><td>PLASTER SPECIFIC HEAT CAPACITY .....</td><td>1000</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) .....</td><td>820</td></tr> <tr><td>THICKNESS (m) .....</td><td>0.110</td></tr> <tr><td>PLASTER THICKNESS .....</td><td>0.019</td></tr> <tr><td>THICKNESS (total) .....</td><td>0.129</td></tr> <tr><td>CONDUCTIVITY (W/mK) .....</td><td>0.71</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) .....</td><td>0.155</td></tr> <tr><td>PLASTER RESISTANCE .....</td><td>0.123</td></tr> <tr><td>RESISTANCE (total) .....</td><td>0.278</td></tr> </table>		PLASTER .....	YES	DENSITY (Kg/m <sup>3</sup> ) .....	1800	PLASTER DENSITY .....	1000	DENSITY (mean) .....	1680	SPECIFIC HEAT CAPACITY (J/KgK) .....	790	PLASTER SPECIFIC HEAT CAPACITY .....	1000	SPECIFIC HEAT CAPACITY (mean) .....	820	THICKNESS (m) .....	0.110	PLASTER THICKNESS .....	0.019	THICKNESS (total) .....	0.129	CONDUCTIVITY (W/mK) .....	0.71	RESISTANCE (m <sup>2</sup> K/W) .....	0.155	PLASTER RESISTANCE .....	0.123	RESISTANCE (total) .....	0.278
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**Table 6.5.1:**

*Properties of wall construction - Site 1 - Wall type D*



**Fig. 6.5.1:**  
*Cross section through the wall construction - Site 1 - Wall type D  
 (Before insulation was injected in the cavity airspace)*



**Fig. 6.5.2:**  
*Cross section through the wall construction - Site 1 - Wall type D  
 (After insulation was injected in the cavity airspace)*



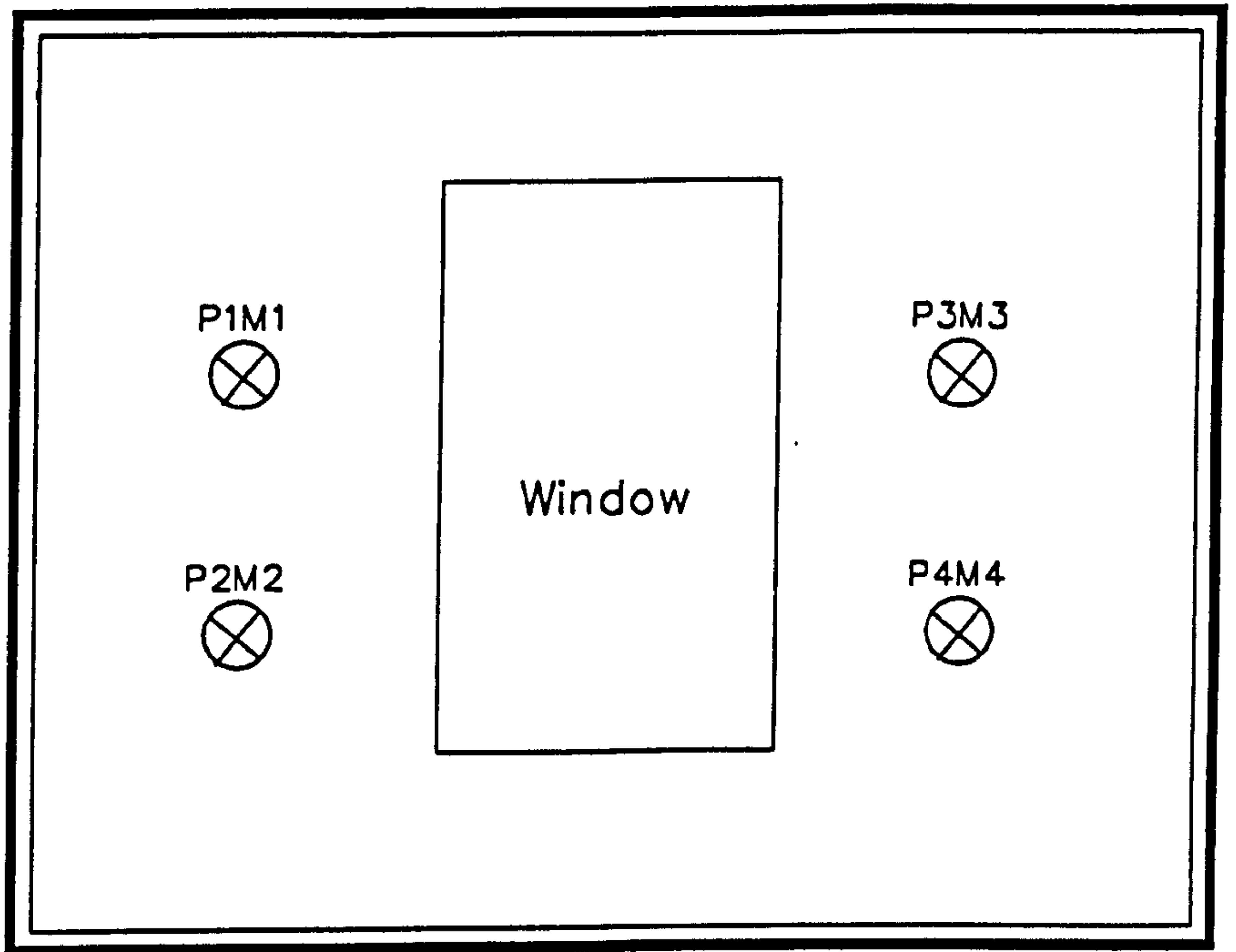


Fig. 6.5.3:

Position of HFSs on the wall surface - Site 1 - Wall type D

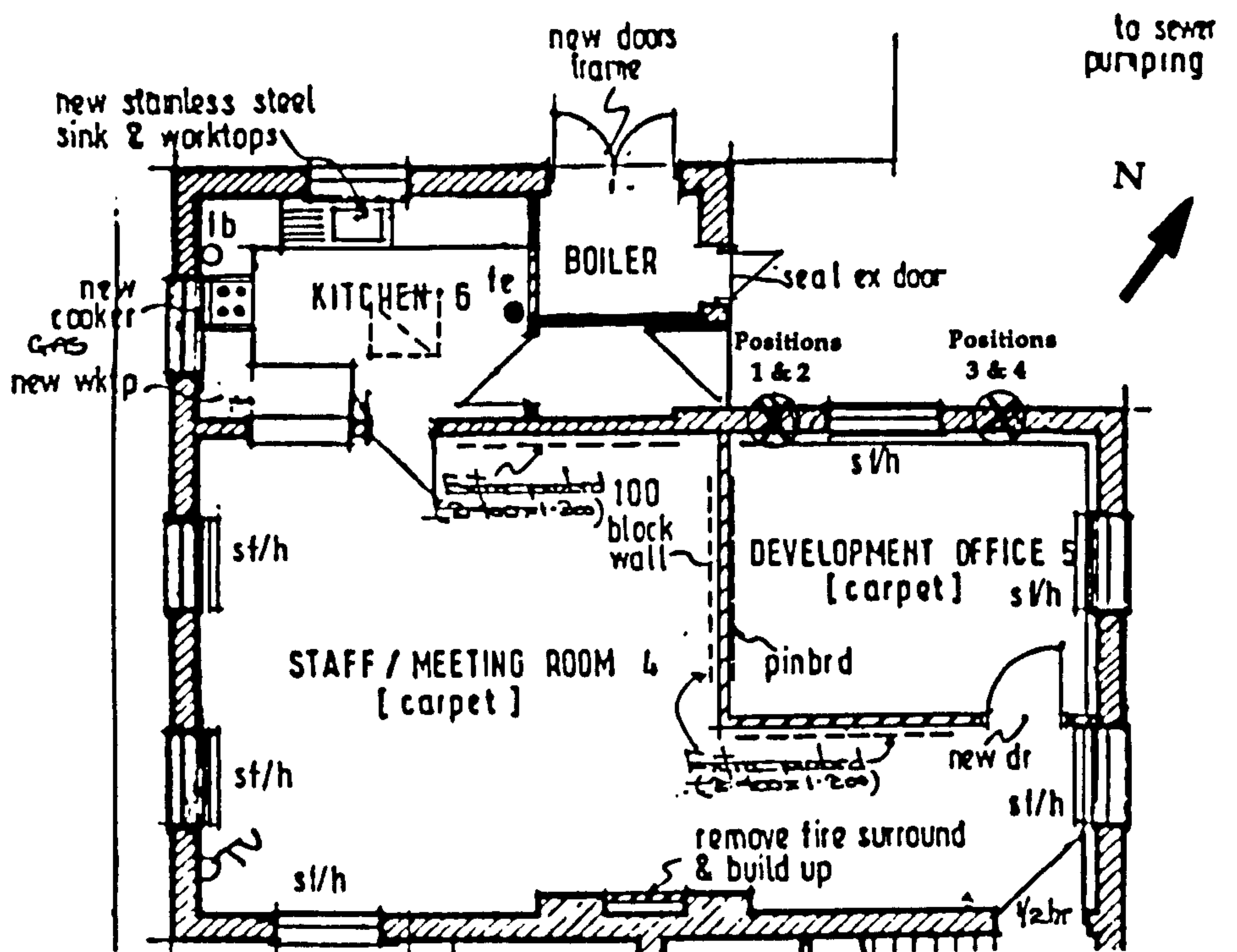


Fig. 6.5.4:

Location of HFSs on the wall surface - Plan view - Site 1 - Wall type D

SITE 1

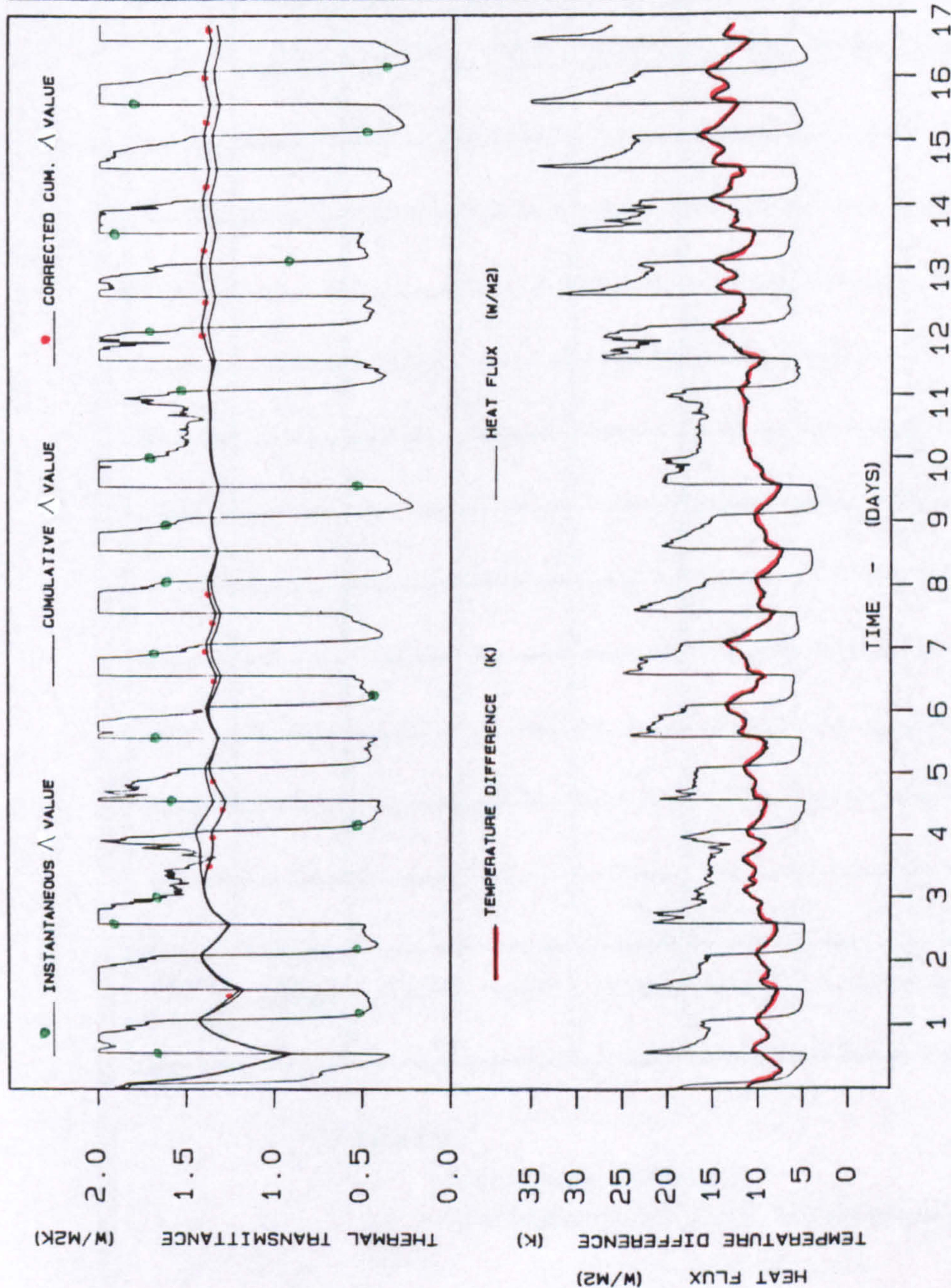
DATA ANALYSIS



Position	Sensor No:	Averaging Method $\Lambda'$ Value			Anderson Method $\Lambda$ Value			Averaging Corrected Value
		Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Anderson Corrected Value
1	66	1.3345	1.3026	1.4146	1.3867	1.3536	1.4700	0.9623
2	64	1.2854	1.2808	1.3909	1.3439	1.3391	1.4543	0.9564
3	69	1.4346	1.4436	1.5677	1.4908	1.5002	1.6292	0.9623
4	68	1.3334	1.3254	1.4394	1.3936	1.3852	1.5043	0.9569
MEAN VALUE ➡		1.3470	1.3381	1.4532	1.4038	1.3945	1.5145	0.9595

Table 6.5.2:  
 Results - Site 1 - Wall type D  
 (Before insulation was injected in the cavity airspace)





START DATE:	10/11/89
END DATE:	27/11/89
DURATION:	17 DAYS
LOCATION:	
MORPETH	
RECORDING INSTRUMENT / No.	
D / 66	
WALL CONSTRUCTION:	
OUTER LEAF:	FACING BRICK
INSULATION:	NO
INNER LEAF:	COMMON BRICK
FILE NAME:	MTH21T.001
COMMENTS:	
MORPETH - HEPSCOTT PARK - TILL HOUSE MUSIC ROOM - GROUND FLOOR - TOP LEFT HFS - 1st SERIES OF MEASUREMENTS, BEFORE INSULATION - NOVEMBER 1989.	
BUILDING SCIENCE SECTION SCHOOL OF ARCHITECTURE NEWCASTLE UNIVERSITY	

Fig. 6.5.5:  
Indicative sample of temperature difference, heat flux, instantaneous  $\lambda$  value, cumulative (Averaging)  $\lambda$  value, corrected (Anderson)  $\lambda$  value - Site 1 - Wall type D (Before insulation was injected in the cavity airspace)







START DATE: 29/11/89
END DATE: 15/12/89
DURATION: 16 DAYS
LOCATION: MORPETH
RECORDING INSTRUMENT / No.: D / 66
WALL CONSTRUCTION: OUTER LEAF: FACING BRICK INSULATION: CYPROC BLOWN WOOL INNER LEAF: COMMON BRICK
FILE NAME: MTH22T.001
COMMENTS: MORPETH - HEPSCOTT PARK - TILL HOUSE 2nd SERIES - MUSIC ROOM - TOP LEFT HFS AT THE LEFT H.S. OF THE WINDOW. AFTER INSULATION. DECEMBER 1989.
BUILDING SCIENCE SECTION SCHOOL OF ARCHITECTURE NEWCASTLE UNIVERSITY

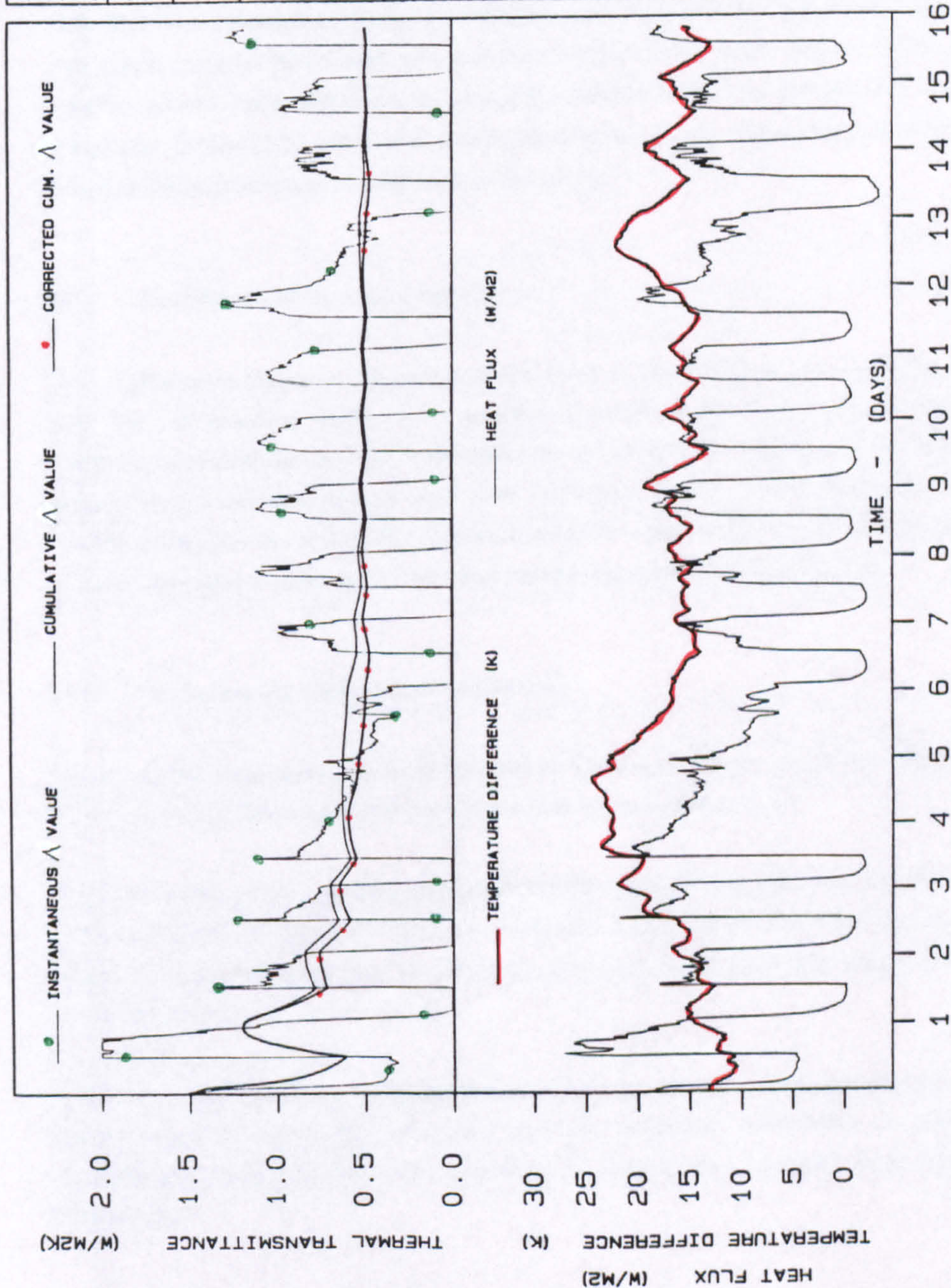


Fig. 6.5.6:

Indicative sample of temperature difference, heat flux, instantaneous  $\Lambda$  value, cumulative (Averaging)  $\Lambda$  value, corrected (Anderson)  $\Lambda$  value - Site 1 - Wall type D (After insulation was injected in the cavity airspace)



### **6.6.0 The measurement (Site 2)**

Six measurements were undertaken at Site 2 which was a laboratory in the 1st floor at Freeman Hospital in Newcastle. The wall was of brick/cavity/lightweight block/plaster construction. The Site was monitored before and after insulation was injected in the cavity.

Table 6.6.1 gives the properties of the wall construction and a section of the wall (before and after insulation was injected in the cavity airspace) is illustrated in Figs. 6.6.1 and 6.6.2. The location of the measurement positions was determined by the availability of space on the wall surface and the requirement to place the sensors on a thermally uniform area of the wall. This was achieved by using the infrared camera so that thermal abnormalities on the wall could be established and avoided. The mortar joints were clearly visible with the infrared camera due to the blockwork having a considerably lower conductivity than that of the mortar. It should be noted that the thermographic survey was employed only once and that was before insulation was injected in the cavity.

#### **6.6.1 Description of the measurement**

Three HFSs were placed at the centre of the block at the positions shown in Fig. 6.6.3 and they were all retained in the same position throughout the 2 monitoring periods. The measurement positions were all in the same north facing wall. A series of two measurement periods was undertaken (before and after Pilkington blown mineral wool insulation was injected in the 65mm cavity). The "before insulation" monitoring period was approximately 11 days. The "after insulation" monitoring period was approximately 16 days.

#### **6.6.2 The measured performance of the wall**

The measured wall performance is detailed in Table 6.6.2 before insulation was injected in the cavity and in Table 6.6.3 after insulation was injected in the cavity.

The corrections applied to the measured values were; firstly, the term for the "relative" calibration of the HFSs and secondly a calculated correction of +5.2% for clear cavity and +3.6% for fully filled cavity, to allow for the heat flow distortion using Trethowen's correlation (chapter 5 - section 5.1.2).

Figs. 6.6.4 and 6.6.5 show the temperature difference, the heat flux through the wall, the instantaneous  $\Lambda$  value, the Averaging and the Anderson cumulative  $\Lambda$  values for a representative measurement point (Position 1 - Site 2) for clear and fully filled cavity respectively.

The conductance values derived using the Averaging and the Anderson methods were found to be close together with the difference between any two values not exceeding 7.7% for any single measurement (Tables 6.6.2 and 6.6.3) and the Anderson values were taken as the appropriate measure of the wall transmittance.

For a clear cavity the best estimate of the average wall performance at the 3 measurement positions (1 to 3) is the mean value of 0.8187 with a 4.45% variation between the upper and lower estimates of the measured wall performance (Table 6.6.4).

For a fully filled cavity the best estimate of the average wall performance at the 3 measurement positions (1 to 3) is the mean value of 0.4065 with a variation of 4.15% between the upper and lower estimates of the measured wall performance (Table 6.6.4).

Position	$\Lambda$ Value (W/m <sup>2</sup> K)  (Before insulation was injected in the cavity airspace)	$\Lambda$ Value (W/m <sup>2</sup> K)  (After insulation was injected in the cavity airspace)	Difference between the two values
1	0.8370	0.4053	0.4317
2	0.8006	0.3884	0.4122
3	0.8185	0.4005	0.4180
Mean value	0.8187	0.4065	0.4206
<b>Table 6.6.4:</b> <i>Transmittance values for a brick/cavity/lightweight block /plaster wall - Site 2</i> <i>Wall type D - (Before and after insulation was injected in the cavity airspace)</i>			

**6.6.3     Determination of the theoretical performance of the wall**

The methods used to calculate the theoretical performance of the wall were:

- (1) the CIBSE 1D model
- (2) the CIBSE area weighted model
- (3) Expected 1D value model
- (4) finite element model



**CIBSE 1D model:**

The  $\Lambda$  value was calculated according to the CIBSE Guide which assumes homogeneous construction by taking into account the thermophysical properties of each separate layer comprising the wall. The best estimate of the  $\Lambda$  value was  $0.76 \text{ W/m}^2\text{K}$  for clear cavity and  $0.35 \text{ W/m}^2\text{K}$  for fully filled cavity using the values in Table 6.6.5.

**CIBSE area weighted model:**

The area weighted model was also used in order to take into account the effect of the mortar joints. The best estimate of the  $\Lambda$  value was  $0.87 \text{ W/m}^2\text{K}$  for a clear cavity and  $0.36 \text{ W/m}^2\text{K}$  for a fully filled cavity assuming a 10mm mortar joint and a block of standard dimensions  $440 * 215 * 100 \text{ mm}$ . The proportions for the block and mortar area was taken as 93.43% and 6.56% respectively.

**Expected 1D value model:**

In order to evaluate the expected performance of the wall after insulation was injected in the cavity airspace, the insulation resistance value of  $1.763 \text{ m}^2\text{K/W}$  was added to the measured average performance of  $1.2214 \text{ m}^2\text{K/W}$  for a clear cavity wall resulting to a mean  $\Lambda$  value of  $0.335 \text{ W/m}^2\text{K}$ .

**Finite element model:**

In order to achieve a better approximation, an additional set of calculations was carried out i.e. a 3D finite element model was applied. Two estimates are presented for the  $\Lambda$  value of the retrofit cavity wall, a block average value of 0.88 and a block centre value of 0.78 for a clear cavity, a block average value of 0.37 and a block centre value of 0.33 for a fully filled cavity. The conditions applied are given in Table 6.6.5.

In the modelling process the wall surface resistances ( $\text{m}^2\text{K/W}$ ) were taken as:

Internal	Cavity	External
0.123	0.09	0.03

<b>Ident: Site 2 - Wall Type D</b>		
<b>Material</b>	<b>Thickness (mm)</b>	<b>Resistance (m<sup>2</sup>K/W)</b>
<b>Brick</b>	100	0.087
<b>Cavity</b>	65	
<b>Insulation</b>	None/fully filled	1.763
<b>Block</b>	150	0.938
<b>Plaster</b>	13	0.110
<b>Mortar joint</b>	150	0.190
<b>Table 6.6.5:</b> <i>Construction details used for thermal modelling - Site 2 - Wall type D</i>		



6.6.4 Comparison between the measured and theoretical transmittance values

The values obtained are shown in Table 6.6.6.

	FE Model ling	CIBSE 1D	Guide Area Weighted	Expected 1D	Measured Value
<b>Site 2 (clear cavity)</b>					
Block average	0.88	X	0.87		
Block centre	0.78	0.76	X	X	0.82
Block average/ Block centre	1.13		1.14		
<b>Site 2 (Fully filled cavity)</b>					
Block average	0.37	X	0.36	X	
Block centre	0.33	0.35	X	0.33	0.41
<b>Table 6.6.6:</b> <i>FE, CIBSE and measured transmittance (W/m<sup>2</sup>K) values for a brick/retrofit cavity/lightweight block/plaster wall - Site 2 - Wall type D</i>					

The CIBSE 1D model assumes homogeneous construction and is expected to be a good estimate of the block centre value. A reasonable correspondence with the FE block centre value is anticipated. The measured value at the block centre is also expected to be in agreement with the theoretical values. This in fact is the case for a clear cavity with the FE block centre, CIBSE 1D and the measured values being 0.78, 0.76 and 0.82 respectively. The same can be said for a fully filled cavity with the FE block centre, CIBSE 1D, expected 1D and the measured values being 0.33, 0.35, 0.33 and 0.41 respectively. The expected 1D value of 0.33 is slightly lower (4.5%) when compared to the CIBSE 1D value of 0.35.

Given the experimental errors and the uncertainty in calculating the theoretical performance due to possible differences in material properties and dimensions between the actual and theoretical walls, the measured value compares very favourably with the theoretical values in both, before and after insulation was injected in the cavity airspace.

On the other hand the CIBSE area weighted model which takes into account the cold bridging is expected to be a good estimate of the block average and a reasonable correspondence with the FE block average is anticipated. Again this is the case for a clear cavity where both models give consistent results with the CIBSE area weighted value being 0.87 and the FE block average value being 0.88. The same can be said for the case of a fully filled cavity where the insulation plays a major role on the average performance of the wall making the effect of the mortar joints negligible. Both models therefore give consistent results with the CIBSE area weighted value being 0.36 and the FE block average value being 0.37.

For a clear cavity the average block performance is greater than the block centre due to the bridging effect. The measured value lies between the upper and lower limits of the calculated block average and block centre values (Table 6.6.6).

From the measured data for a clear cavity the best estimate of the measured average wall performance to take the bridging effect into account, is to take the ratio of the FE average to the centre value of 1.13 and to multiply by the measured centre block value. This gives a result of 0.93 which is in close agreement with the FE and CIBSE block average values.

There is a marginal variation in the measured values of some 4.45% for a clear cavity and 4.15% for a fully filled cavity for the values recorded. This is in line with the variation to be expected due to changes in the material properties and dimensional tolerances of the wall calculated according to Pentz and Shott method of  $\pm 4.2\%$  and  $\pm 6.70\%$  for a clear and fully filled cavity respectively (chapter 4) and experimental error.

Finally, the evidence is that wall behaves according to the design specifications. This is true for both cases: before and after insulation was injected in the cavity airspace.

In the case of a clear cavity if the value resulting from the CIBSE 1D model which is traditionally employed as a design tool, is compared with the estimated measured value, it underestimates the average performance of the wall by some 22%. From this study the best estimate of the measured average wall performance is 0.93, which is in close agreement with the CIBSE area weighted value of 0.87 and the FE block average value of 0.88.



For a fully filled cavity the insulation layer forms the major contributory factor to the total resistance/performance of the wall structure and the effect of the bridging by the mortar joints on the average performance of the wall becomes negligible. The best estimate of the measured average wall performance is 0.41, which is in close agreement with the CIBSE area weighted value of 0.36 and the FE block average value of 0.37.

**SITE 2**

**WALL DETAILS**

**PHYSICAL DESCRIPTION**

**OF**

**THE WALL**

**AND**

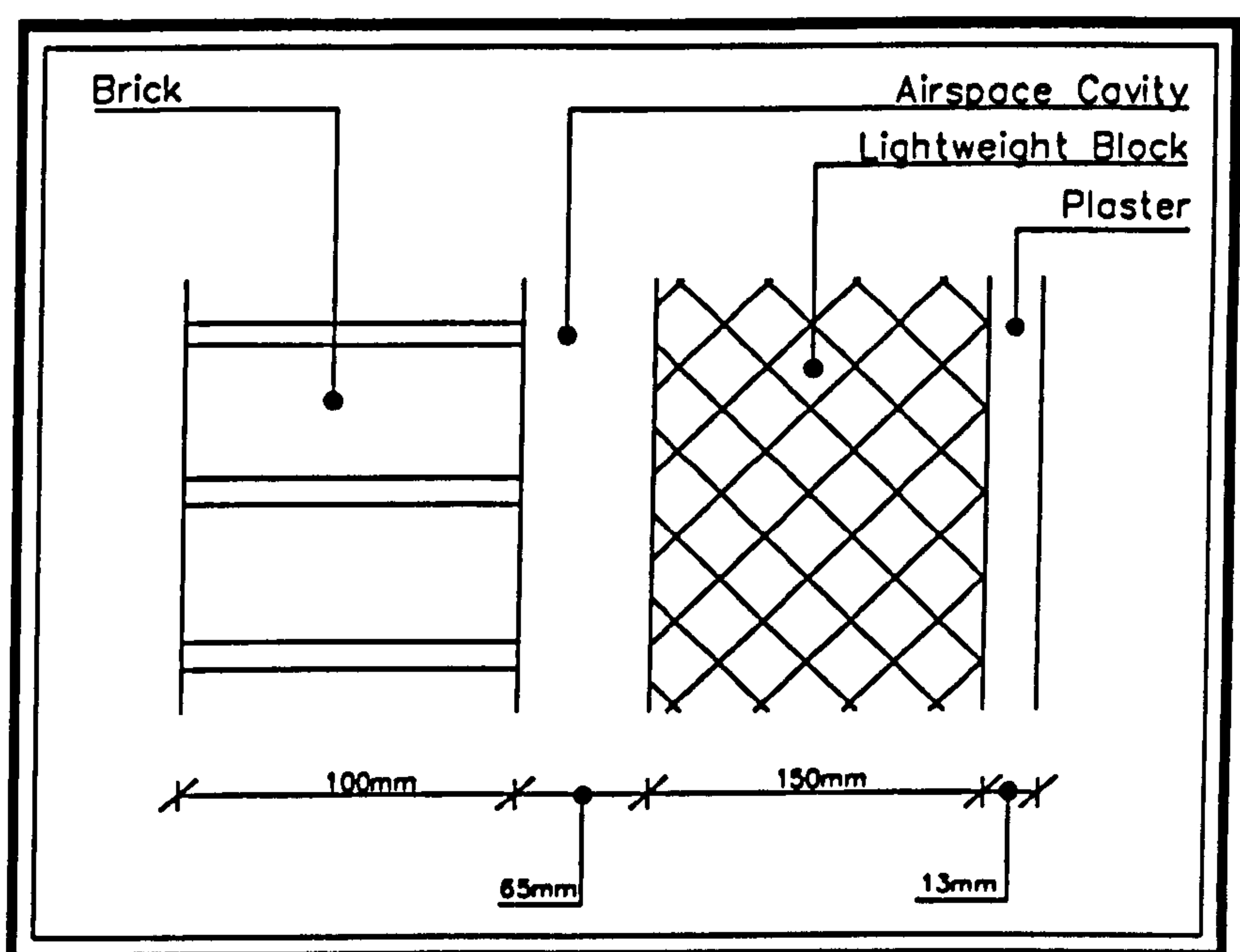
**LOCATION OF HFSs**



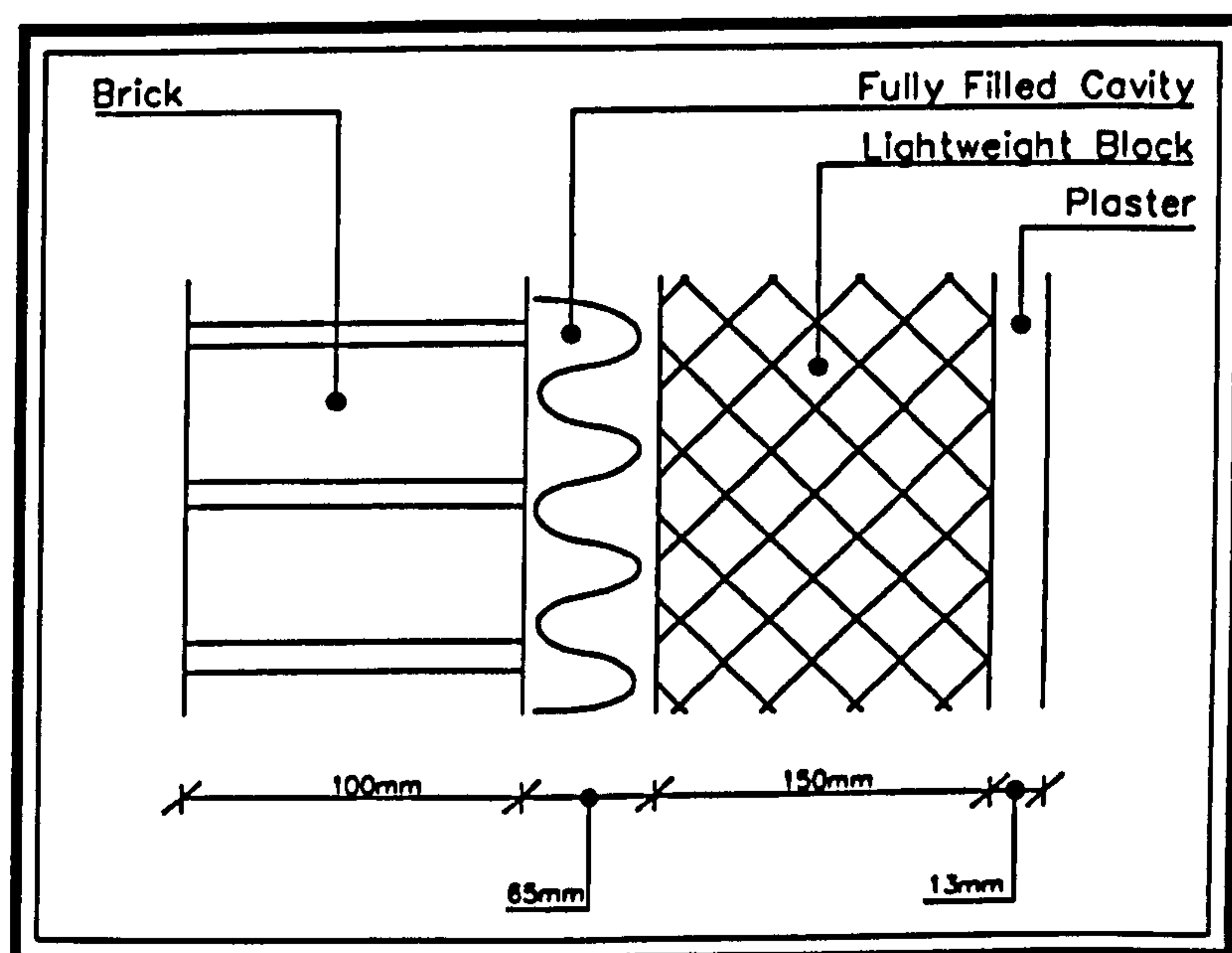
<div style="border: 1px solid black; padding: 2px;"> ID : Wall type D Site 2 </div>	<h2 style="margin: 0;">PROPERTIES OF WALL CONSTRUCTION</h2>																												
<div style="margin-bottom: 10px;"> <b>SITE :</b>    FREEMAN HOSPITAL - MICROBIOLOGY LAB. </div> <div style="display: flex; justify-content: space-between; margin-bottom: 10px;"> <span><b>SITE No.:</b></span> <span><b>SERIES OF MEASUREMENT :</b></span> <span><b>DATE :</b> WINTER 1988</span> </div> <div style="display: flex; justify-content: space-between;"> <span><b>CONSTRUCTION YEAR:</b> 1972</span> <span><b>FILENAME:</b></span> </div>																													
<div style="margin-bottom: 10px;"> <b>INNER LEAF : "DUROX" BLOCKWORK</b> </div> <table style="width: 100%; border-collapse: collapse;"> <tr><td style="width: 80%;">PLASTER .....</td><td style="text-align: right;">YES</td></tr> <tr><td>DENSITY (Kg/m<sup>3</sup>) .....</td><td style="text-align: right;">600</td></tr> <tr><td>PLASTER DENSITY .....</td><td style="text-align: right;">770</td></tr> <tr><td>DENSITY (mean) .....</td><td style="text-align: right;">612</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) .....</td><td style="text-align: right;">950</td></tr> <tr><td>PLASTER SPECIFIC HEAT CAPACITY .....</td><td style="text-align: right;">1000</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) .....</td><td style="text-align: right;">952</td></tr> <tr><td>THICKNESS (m) .....</td><td style="text-align: right;">0.150</td></tr> <tr><td>PLASTER THICKNESS .....</td><td style="text-align: right;">0.013</td></tr> <tr><td>THICKNESS (total) .....</td><td style="text-align: right;">0.163</td></tr> <tr><td>CONDUCTIVITY (W/mK) .....</td><td style="text-align: right;">0.16</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) .....</td><td style="text-align: right;">0.938</td></tr> <tr><td>PLASTER RESISTANCE .....</td><td style="text-align: right;">0.110</td></tr> <tr><td>RESISTANCE (total) .....</td><td style="text-align: right;">1.048</td></tr> </table>		PLASTER .....	YES	DENSITY (Kg/m <sup>3</sup> ) .....	600	PLASTER DENSITY .....	770	DENSITY (mean) .....	612	SPECIFIC HEAT CAPACITY (J/KgK) .....	950	PLASTER SPECIFIC HEAT CAPACITY .....	1000	SPECIFIC HEAT CAPACITY (mean) .....	952	THICKNESS (m) .....	0.150	PLASTER THICKNESS .....	0.013	THICKNESS (total) .....	0.163	CONDUCTIVITY (W/mK) .....	0.16	RESISTANCE (m <sup>2</sup> K/W) .....	0.938	PLASTER RESISTANCE .....	0.110	RESISTANCE (total) .....	1.048
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RESISTANCE (total) .....	1.048																												
<div style="margin-bottom: 10px;"> <b>OUTER LEAF : JACOBAN FACING BRICKS</b> </div> <table style="width: 100%; border-collapse: collapse;"> <tr><td style="width: 80%;">RENDER ? .....</td><td style="text-align: right;">NO</td></tr> <tr><td>DENSITY (kg/m<sup>3</sup>) .....</td><td style="text-align: right;">2094</td></tr> <tr><td>RENDER DENSITY .....</td><td></td></tr> <tr><td>DENSITY (mean) .....</td><td style="text-align: right;">2094</td></tr> <tr><td>SPECIFIC HEAT CAPACITY (J/KgK) .....</td><td style="text-align: right;">800</td></tr> <tr><td>RENDER SPECIFIC HEAT CAPACITY .....</td><td></td></tr> <tr><td>SPECIFIC HEAT CAPACITY (mean) .....</td><td style="text-align: right;">800</td></tr> <tr><td>THICKNESS (m) .....</td><td style="text-align: right;">0.100</td></tr> <tr><td>RENDER THICKNESS .....</td><td></td></tr> <tr><td>THICKNESS (total) .....</td><td style="text-align: right;">0.100</td></tr> <tr><td>CONDUCTIVITY (W/mK ) .....</td><td style="text-align: right;">1.15</td></tr> <tr><td>RESISTANCE (m<sup>2</sup>K/W) .....</td><td style="text-align: right;">0.087</td></tr> <tr><td>RENDER RESISTANCE .....</td><td></td></tr> <tr><td>RESISTANCE (total) .....</td><td style="text-align: right;">0.087</td></tr> </table>		RENDER ? .....	NO	DENSITY (kg/m <sup>3</sup> ) .....	2094	RENDER DENSITY .....		DENSITY (mean) .....	2094	SPECIFIC HEAT CAPACITY (J/KgK) .....	800	RENDER SPECIFIC HEAT CAPACITY .....		SPECIFIC HEAT CAPACITY (mean) .....	800	THICKNESS (m) .....	0.100	RENDER THICKNESS .....		THICKNESS (total) .....	0.100	CONDUCTIVITY (W/mK ) .....	1.15	RESISTANCE (m <sup>2</sup> K/W) .....	0.087	RENDER RESISTANCE .....		RESISTANCE (total) .....	0.087
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RESISTANCE (total) .....	0.087																												
<div style="display: flex; justify-content: space-between; margin-bottom: 5px;"> <span>CAVITY ?YES(65mm)</span> <span>VENTILATED CAVITY? NO</span> <span>INSULATION?</span> </div> <div style="display: flex; justify-content: space-between;"> <div style="width: 40%;"> CAVITY RESISTANCE:0.180 (without 1.763 (with insulation) </div> <div style="width: 60%;"> INSULATION RESISTANCE: HFS CALIBRATION FACTOR: </div> </div>																													

**Table 6.6.1:**

*Properties of wall construction - Site 2 - Wall type D*

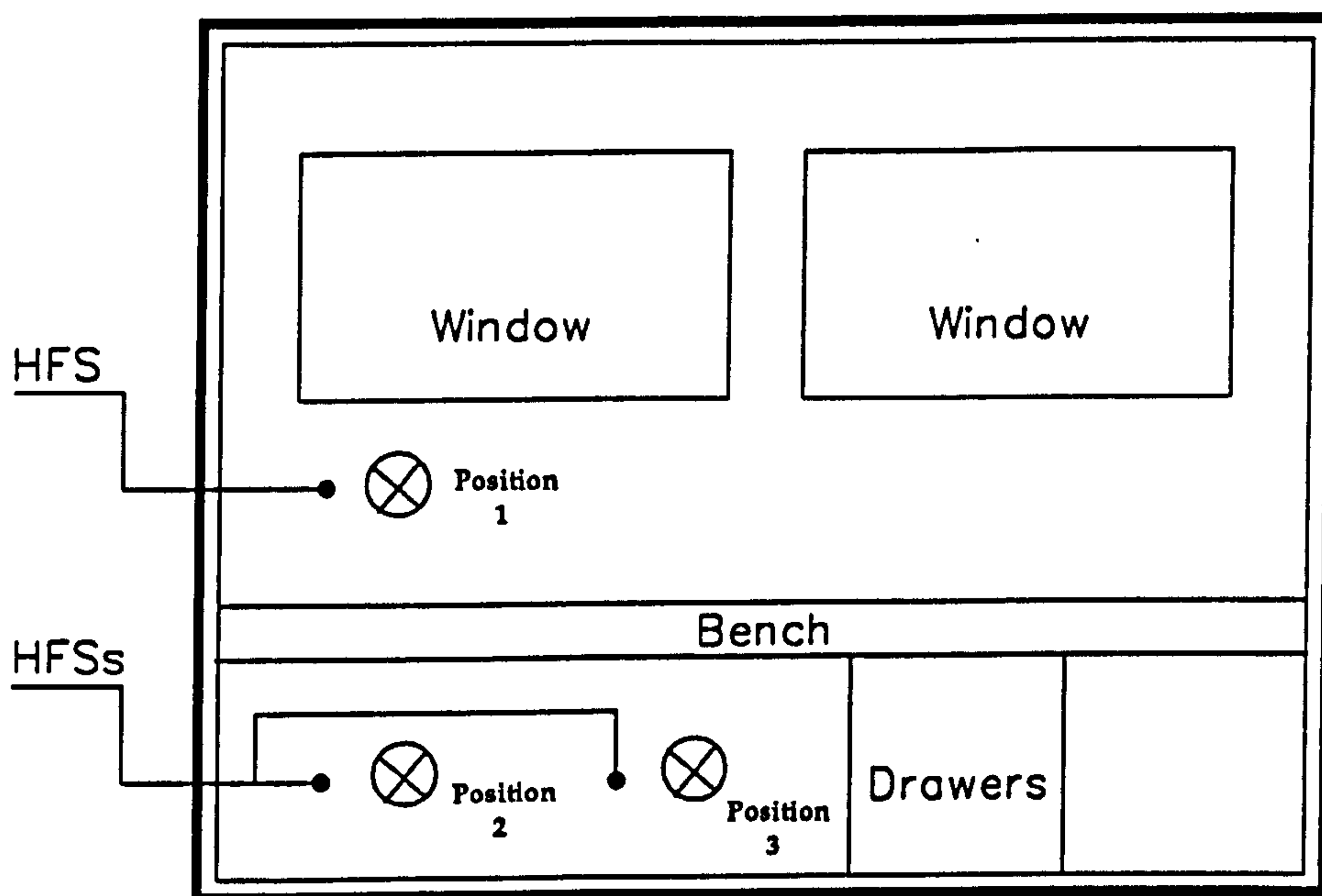


**Fig. 6.6.1:**  
*Cross section through the wall construction - Site 2 - Wall type D  
 (Before insulation was injected in the cavity airspace)*



**Fig. 6.6.2:**  
*Cross section through the wall construction - Site 2 - Wall type D  
 (After insulation was injected in the cavity airspace)*





**Fig. 6.6.3:**  
*Position of HFSs on the wall surface - Site 2 - Wall type D*

**SITE 2**

**DATA ANALYSIS**



Position	Sensor No:	Averaging Method $\Lambda$ Value			Anderson Method $\Lambda$ Value			Averaging Corrected Value $\frac{\text{Averaging Corrected Value}}{\text{Anderson Corrected Value}}$
		Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	Un-corrected	Sensor Calibration Correction	Heatflow Distortion Correction	
1	64	0.8375	0.8345	0.8779	0.7985	0.7956	0.8370	1.0489
2	67	0.8358	0.8241	0.8670	0.7708	0.7610	0.8006	1.0829
3	70	0.8477	0.8398	0.8835	0.7853	0.7780	0.8185	1.0794
MEAN VALUE ➡		0.8403	0.8328	0.8761	0.7852	0.7782	0.8187	1.0701

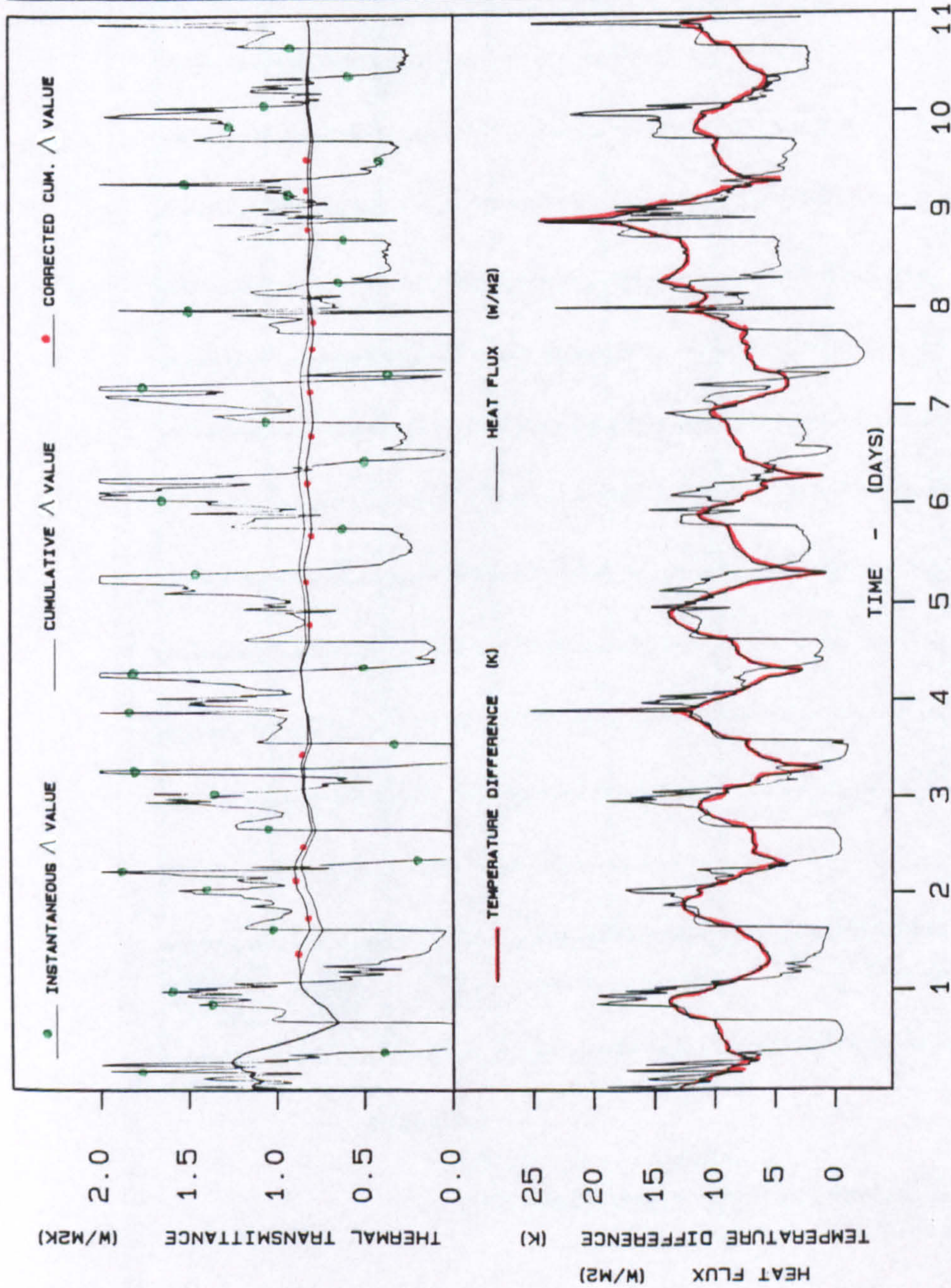
**Table 6.6.2:**

### Results - Site 2 - Wall type D

*(Before insulation was injected in the cavity airspace)*



START DATE: 31/03/88
END DATE: 11/04/88
DURATION: 11 DAYS
LOCATION: FREEMAN HOSPITAL
RECORDING INSTRUMENT / No. 07
WALL CONSTRUCTION: OUTER LEAF: JACOBSEAN BRICKWORK INSULATION: NO INNER LEAF: DUROX BLOCK+ PLASTER
FILE NAME: FH8MLU.001
COMMENTS: THESE DATA WERE RECORDED BEFORE INSULATION WAS INSTALLED IN THE WALL. THE DATA ARE FROM THE UPPER MAT. NO MOISTURE READINGS ARE AVAILABLE. FREEMAN HOSPITAL - MICROBIOLOGY LAB PATHOLOGY DEPARTMENT - ROOM 101
BUILDING SCIENCE SECTION SCHOOL OF ARCHITECTURE NEWCASTLE UNIVERSITY



**Fig. 6.6.4:**  
*Indicative sample of temperature difference, heat flux, instantaneous  $\Delta$  value, cumulative (Averaging)  $\Delta$  value, corrected (Anderson)  $\Delta$  value - Site 2 - Wall type D (Before insulation was injected in the cavity airspace)*







START DATE: 18/04/88
END DATE: 04/05/88
DURATION: 16 DAYS
LOCATION: FREEMAN HOSPITAL
RECORDING INSTRUMENT / No. 04
WALL CONSTRUCTION: OUTER LEAF: JACOBAN BRICK INSULATION: MINERAL FIBRE INNER LEAF: DUROX BLOCK+ PLASTER
FILE NAME: FHMLU.001
COMMENTS: FREEMAN HOSPITAL - PATHOLOGY DEPARTM MICROBIOLOGY SECTION - ROOM 101 THESE RESULTS ARE FROM THE UPPER MAT AFTER INSULATION.
BUILDING SCIENCE SECTION SCHOOL OF ARCHITECTURE NEWCASTLE UNIVERSITY

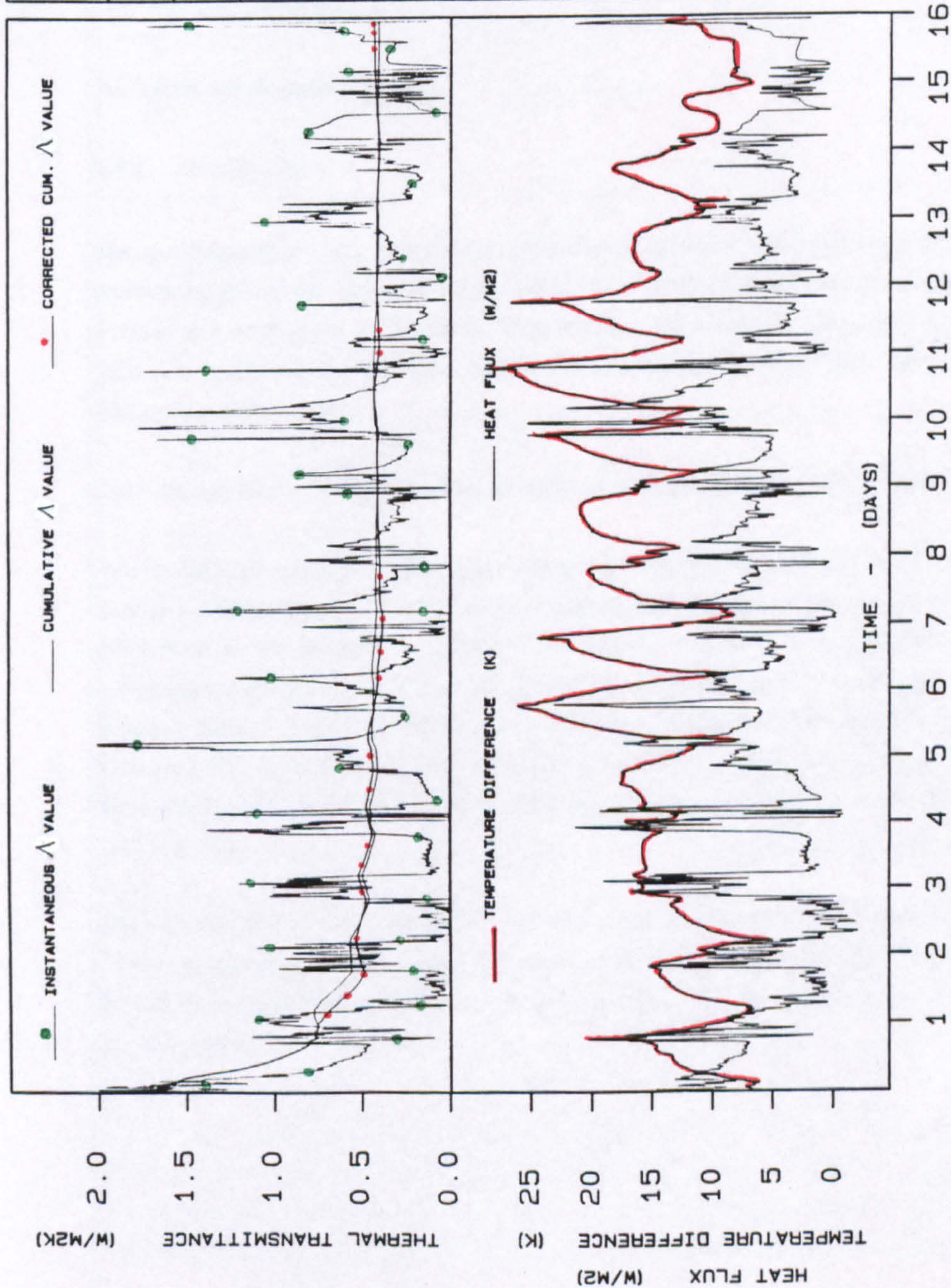


Fig. 6.6.5:

Indicative sample of temperature difference, heat flux, instantaneous  $\Lambda$  value, cumulative (Averaging)  $\Lambda$  value, corrected (Anderson)  $\Lambda$  value - Site 2 - Wall type D (After insulation was injected in the cavity airspace)



## **6.7 Conclusions**

This chapter has detailed investigations into 4 generic wall types including clear, partially filled and fully filled cavities. This concluding section brings together the individual results to provide an overview of the major issues involved in the evaluation of wall performance, namely:

- (1) partitioning of the observed variability in wall performance
- (2) the validity of the calculation methods
- (3) the wall performance

All issues are discussed in turn.

### **6.7.1 Variability**

An understanding of the variability in the observed wall performance can be obtained from examining the variability in the measurements of wall performance where the sensors were rotated for wall types A, B and C. This enabled the observed variability to be partitioned into two components, (i) that due to the measurement itself and (ii) that due to the behaviour of the wall:

- (i) the variability involved in the process of measuring the wall behaviour

The variability involved in the measurement process can be partitioned into systematic and random effects. The systematic effect is introduced because, while the sensor set had been calibrated in the chamber experiment (chapter 5 - section 5.1.1) systematic differences in calibration may still exist. This is confirmed by the Analysis of Variance carried out for wall types A (Sites 1, 2 & 3), B and C where significant differences between the sensor sets were obtained (S/Tables 6.1.1 to 6.1.3, 6.2.1 and 6.3.1). The spread of the observed values ranged from 0.01% to 12% for wall type A, 15% for wall type B and 11% for wall type C - Site 1 (Table 6.7.1).

This means that if only one sensor set was used to carry out the measurement there is a "built in" systematic error. Given the worst case condition of a range of 15% this is likely to introduce a maximum systematic error of  $\pm 7.5\%$  about the mean value of the "true" wall performance.

Wall Type (Construction)	Variability Between Sensor Sets	
	Systematic Errors at each measurement Site (max/min)	Random Errors (standard error for a single transmittance measurement)
A (brick/cavity/"Polyblox"/ plaster)	Site 1: 0.01% (2) Site 2: 6.0% (3) Site 3: 12.0% (3)	Site 1: 3.98% Site 2: 2.35% Site 3: 2.85%
B (brick/clear cavity/aerated block/plaster)	Site 1: 15.0% (4)	Site 1: 2.00%
C (brick/partially filled cavity/ block/plaster)	Site 1: 11.0% (5)	Site 1: 2.70%
<b>Note:</b> the figure in ( ) indicates the number of rotating sensors		
<b>Table 6.7.1:</b> <i>Variability between sensor sets for wall types A, B &amp; C</i>		

The random effects are accounted for by the standard error of measurement. An indication of the random error introduced by the attachment of the sensors on the wall surface and of all the other random sources of variation in the measurement process was obtained by the residual mean square in the Analysis of Variance Tables (S/Tables 6.1.1 to 6.1.3 and 6.2.1 and 6.3.1). This is the uncertainty associated with a single transmittance measurement. An estimate of the magnitude is given in Table 6.7.1.

This was 3.1% (pooled variance) for wall type A, 2% for wall type B and 2.7% for wall type C. The overall pooled variance across all Sites which may be taken as the mean best estimate gives a standard error of 2.65%. This gives 99% confidence limits of +/-8%.

Contained within the above is the variability in the environmental conditions which involves a random error impossible to establish on an individual basis. However an indication is provided by the standard error in a single transmittance measurement which includes the change in the environmental conditions at the particular point.



If a sensor set is selected at random the systematic error introduced can be considered as a random effect and the combined estimate of variability for a single measurement is therefore the combination of both:

$$\sqrt{7.5^2 + 8^2} = +/-11\% \text{ (for 99\% confidence limits)}$$

That is, a single measurement will be within +/-11% of the "true" value for a perfect wall.

(ii) the variability in the wall behaviour (between different wall positions)

For all wall types there were significant differences between the wall positions (S/Tables 6.1.1 to 6.1.3 and 6.2.1, 6.3.1). An indication of the variability involved in the performance of the wall is given by the range in the observed values which varied from 4% (wall type D - Site 2) to 39.5% (wall type A) [Table 6.7.2].

Wall Type (Construction)	Range in Values Between Wall Positions (max-min/mean)
A (brick/cavity/"Polyblox"/plaster)	39.5% (over 9 positions)
B (brick/clear cavity/aerated block/plaster)	25.5% (over 3 positions)
C (brick/partially filled cavity/block/plaster)	10% (over 3 positions)
D (brick/retrofit cavity/brick or block/plaster)	Site 1: 10.7% (before insulation) Site 1: 7.0% (after insulation)  Site 2: 4.45% (before insulation) Site 2: 4.15% (after insulation)
<b>Table 6.7.2:</b> <i>Variability in the wall behaviour (Rotating sensor sets for wall types A, B, &amp; C)</i>	

Inspection of Table 6.7.2 reveals that when a homogeneous layer is integrated within the wall structure, such as, a layer of insulation in an either partially filled or fully filled cavity, the variation between the resulting values is reduced.

The differences in the observed wall performance in different positions may be potentially attributed to 4 major causes, namely:

- (a) Dimensional tolerances and material properties
- (b) Changes in material properties
- (c) The wall as part of a construction
- (d) Workmanship

To gain a better insight of the influence of the above parameters on the final transmittance value that each potential source of variation has to be examined individually.

**(a) Dimensional tolerances and material properties**

The uncertainty introduced by the dimensional tolerances of the physical dimensions and thermal properties of the materials cannot be evaluated directly. They are the intrinsic properties of the wall at a given position. However, the estimate in chapter 4 of the uncertainty introduced in the final  $\Lambda$  value is approximately  $\pm 4\%$  for a clear or partially filled cavity and  $\pm 7\%$  to  $\pm 12\%$  for a fully filled cavity depending upon the cavity thickness.

**(b) Changes in material properties**

Changes in the moisture content and mean temperature of the wall can be expected to vary the conductivity of the materials during the test. This in turn will result in changes in the material properties and in the transmittance value. The variability introduced from these sources is difficult to estimate but an indication may be gained from the resulting values from the HFSs that were retained in the same position throughout the monitoring period (Table 6.7.3). In general, the total monitoring period consisted of 6 consecutive weeks (2 weeks interval  $\times$  3). The HFS rotation pattern was applied at the end of each 2 weeks interval.

For these positions, the differences between resulting values can be principally attributed to changes in the environmental conditions at the particular measurement position, changes in material properties and to any differences introduced by the analysis technique. This consequently provides an upper estimate of the variability introduced by changes in the material properties. The maximum values were 4% for wall type A, 6.4% for wall type B and 6.5% for wall type C - Site 1.



Wall Type (Construction)	Range in Values Between Wall Positions (max-min/mean)
A (brick/cavity/"Polyblox"/plaster)	Site 1: 3.2% Site 2: 0.8% Site 3: 6.0%
B (brick/clear cavity/aerated block/plaster)	Site 1: 6.4%
C (brick/partially filled cavity/block/plaster)	Site 1: 6.5%
<b>Table 6.7.3:</b> <i>Variability in the wall behaviour (Stable sensor sets for wall types A, B &amp; C)</i>	

**(c) The wall as part of a construction**

When thermal transmittance measurements are carried out, the inherent assumption is, that a plain part of the wall is being measured. Great care is taken to ensure that the measurement is carried out at a position which is representative of the wall (i.e. avoiding cold bridging by means of thermographic equipment). Nevertheless, the wall is always measured *as part* of a construction under a given set of uncontrolled environmental conditions. These will introduce an element of variability into the measurement and subsequently into the evaluation of wall performance. A separate estimate of the variability introduced from this source could not be made for the other wall types.

An indication is given in the concluding section of wall type A where the HFSs placed at the upper part of the wall surface always record higher than the HFSs placed at the lower part of the wall, i.e. 19% for Site 1, 4% for Site 2 and 9% for Site 3.

**(d) Workmanship**

When higher than expected  $\Lambda$  values are recorded, they may be due to workmanship. It has been indicated in the course of this study that for all wall types monitored workmanship has a major role to play in the performance of the wall. On-site and boroscopic observations revealed that in many instances the cavities were bridged by building debris, as well as, missing, damaged or misplaced insulation (Plates 6.1.3 to

6.1.10, 6.3.1 to 6.3.3, 6.4.1). Defects such as these result in the wall having variable transmittance at different positions, and consequently, affect the average performance of the wall. A separate estimate of the variability introduced from these sources could not be made.

Four causes were identified which may account for the observed variability in the wall behaviour. On the basis of the above, the variability of types (a) and (b) will seem to fall within limits typically of the order of 8% and 6% respectively). It is not possible to determine individual estimates for (c) and (d). However, an indication for (c) is provided for wall type A by the resulting values from the HFSs placed at the upper and lower parts of the wall respectively. In this case the average value over the 3 Sites was approximately 12%.

Looking at the order of magnitude for the variability introduced by (a), (b), (c), (d)

(a) = 8% (dimensional tolerances and material properties -  
theoretically estimated value - chapter 4)

(b) = 6% (changes in material properties - estimated from measured value)

(a) + (b) is typically of the order  $\sqrt{8^2 + 6^2} = +/-10\%$

(c) = depends upon the individual wall construction (estimated from measured  
value - only for wall type A, approximately 12%)

(d) = not possible to estimate separately

It is reasonable to assume therefore that factors other than workmanship will introduce an element of variability of the order of 10% in transmittance measurements. Consequently, when the variability exceeds 10% there is a probability that the higher values may be attributed to either the construction or the workmanship factor. This is the case with wall types A and B of the present study with a variability of 39.5% and 25.5% respectively, where it may be said that both walls suffer significantly from workmanship defects. In other words, when an element of variability above 10% is encountered, individual values must be subject to scrutiny.

Overall, the nature of the constructions measured and the measurement process itself indicated the following:

- (1) The magnitude of the variability in the wall performance is dependent upon the particular wall type.
- (2) The differences in the measured wall behaviour between different positions are significant.
- (3) The detailed examination of the case studies served to highlight the difficulty of interpretation.



### **6.7.2 Validity of the calculation methods**

The principal sources of uncertainty involved in the application of calculation methods are:

- (a) the appropriateness of the model and
- (b) the input parameters for the model

#### **(a) the appropriateness of the model**

In considering the appropriateness of the model a distinction should be drawn between a design calculation and a calculation which is undertaken either in order to give the best estimate of the heat flow or to gain a better understanding of the wall behaviour.

The standard design calculation method in UK is the CIBSE 1D model (chapter 4) which is used extensively by designers and industry does not take into account, for example, cold bridges or mortar joints. It is not a requirement of the current Building Regulations in England and Wales (Building Regulations - 1990) to take into account in the calculation methods these effects. As expected therefore while the CIBSE 1D model is adequate for simple layered wall constructions which are relatively homogeneous it fails to give adequate representation for non-homogeneous constructions, such as, "Polyblox" or a wall construction where the inner leaf consists of aerated blockwork.

Consequently, the CIBSE 1D calculation model may be used for simple layered wall constructions which are relatively homogeneous.

The CIBSE area weighted or 3D modelling must be used where the wall construction is non-homogeneous i.e. the area weighted model is applicable for walls which consist of aerated blocks in the inner leaf so that the effect of the mortar joints can be taken into account.

The criterion for choosing the right calculation method is the block to mortar conductivity ratio for wall constructions having differential conductivity between block and mortar.

#### **(b) the input parameters for the model**

All models whether they are 1D, 2D or 3D embody the fundamental problems of correctly specifying the dimensions of the wall and the thermophysical properties of the materials and providing appropriate boundary conditions in the cavity airspace (chapter 4).

Although FE modelling is capable of representing complex 3D heat transfer processes, numerical and physical assumptions still have to be made. These models are normally applied to idealised wall constructions and do not take into account the following:

- (i) changes in material properties
- (ii) the wall as part of a construction
- (iii) workmanship

Consequently, the combination of all the above parameters mean that in practice the calculated and measured values will be in good agreement.

### **6.7.3 The mean wall performance**

The main assumptions with respect to the values resulting from the measurement and the calculation, is that, the value which results from the measurement represents the mean wall performance and the value which results from the calculation represents/predicts the expected behaviour of the wall. Taking into account the uncertainties introduced in the calculation and in the measurement the expectation is that the two values never agree.

The calculation methods recommended by the CIBSE Guide which are adopted and used by all construction industry were found to be adequate for simple wall geometries. However, where complex geometry is involved (as in the "Polyblox" case/wall type A) the methods fail to provide a value that may be taken as a reliable indicator of the wall's thermal performance. In particular:

When considering the mean wall performance of wall type A (brick/cavity/"Polyblox" block/plaster) the CIBSE 1D model is definitely not the model to use under these circumstances because it seriously underestimates the average performance of the wall by approximately 34%. Neither is the CIBSE area weighted model, although it may be used in the absence of 2D or 3D facilities. Close correspondence between the measured and the predicted values was indicated only in the case where 3D modelling was used (Table 6.7.4).

When considering the mean wall performance of wall type B (brick/clear cavity/aerated block/plaster) where the inner leaf consists of lightweight/aerated blocks the CIBSE 1D model must not be used because it underestimates the average performance of the wall. The area weighted model is more representative of the average wall performance and it usually has a T value of approximately 20% higher compared with the CIBSE 1D value. This is due to the effect of the mortar joints as predicted by the CIBSE Guide - Section A3. Close correspondence between the measured and the predicted values was indicated in the case where the CIBSE area weighted model and 3D modelling were used (wall types B and D/before insulation was injected in the cavity airspace) [Table 6.7.4].



When considering the mean wall performance of wall type C (brick/ partially filled cavity/ block/plaster) where a layer of insulation was included in the cavity airspace the CIBSE 1D model may be applied with some confidence. Close correspondence between the measured and the predicted values was indicated in the case of all models used (wall type C) [Table 6.7.4].

Finally, when considering the mean wall performance of wall type D where experiments were carried out before and after insulation was injected in the cavity airspace (brick /retrofit cavity/brick or block/plaster) the evidence is that where cavities have been filled with insulation the improved performance was as expected:

The thermal transmittance through the wall was reduced by  $\frac{2}{3}$  after insulation was injected in the cavity of a brick/cavity/brick/plaster wall (wall type D - Site 1) and by  $\frac{1}{2}$  after insulation was injected in the cavity of a brick/cavity/lightweight block/plaster wall (wall type D - Site 2) [Table 6.7.4].

From the above (wall types C & D) it may be deduced therefore that where a layer of insulation (either in a partially or fully filled cavity) is integrated in the structure, the CIBSE 1D is a reliable indicator of the average performance of the wall and it can be used with a degree of confidence at the design stage, using the manufacturers values.

Looking at Table 6.7.4, there is good agreement between the best theoretical estimate which results from the 3D FE modelling and the measured  $\Lambda$  values.

#### **6.7.4 Understanding the wall behaviour by means of an appropriate experimental design procedure**

Chapter 6 has demonstrated that understanding the behaviour of wall constructions in practice is extremely complex. It has also illustrated that measuring one single point/position on the wall is insufficient if a representative value of wall performance is required.

It is clear that there is a need to define an experimental procedure which is capable of generating the necessary information. Different experiments may be designed depending upon the information that it is needed. However, in order to design the appropriate experiment a good understanding of the needs of the particular project is necessary. For example:

Where the objective is simply to determine the average performance of the wall this can be achieved by taking the average value over a number of wall positions. Providing the sample is large enough the measurement errors and the difference in wall positions will be averaged out. For example, for the worst case experiment of the present study the best estimate of the standard error associated with the overall variability for both sensors and positions for wall type A - Site 1 has a value of 14% for 99% confidence limits. This is derived using the mean square of all wall/sensor combinations:  $\sqrt{15.15 \times 10^{-3}}/0.8572$  (page 6.6 - S/Table 6.1.1).

The number of measurements required to obtain the required degree of certainty in the mean wall performance is given by  $14/\sqrt{n}$  where n is the number of measurements. In this case in order to obtain a degree of certainty for the final value within +/-5%, seventy four measurements have to be carried out on the same wall. Note that this experiment will give an indication of the overall variability i.e. that due to the measurement process and that due to the wall performance and does not allow partitioning between the two.

Where the objective is to establish the variability involved in the measurement process and the wall performance a statistical approach must be adopted, such as the factorial design underlying the rotation experiment, because it enables separation of the variability in the measurement and the variability in the wall behaviour (differences between sensor sets and differences between wall positions).

If only a simple measure of the change in the transmittance value is needed, the "before and after insulation" experiment (wall type D) is suitable means of determining the effect. A single point/position is considered to be good enough to make an approximate evaluation of the change. In this case by definition there is no variability due to differences in wall positions or to measurement errors. Sequential measurements have been shown to be robust with only a 6% variation being recorded between stable sensors (Table 6.7.3). Provided the expected change in wall performance is large in comparison to this figure (6%) then any change should be reliably detected. However, if the distribution of the values needs to be determined several points/positions must be measured before a reliable indication of the mean wall performance can be determined.



Wall Type (Construction)	CIBSE 1D "Λ" Value (W/m <sup>2</sup> K)	CIBSE Area Weighted Value (W/m <sup>2</sup> K)	FE Wall Average (W/m <sup>2</sup> K)	Measured "Λ" Value (*) (W/m <sup>2</sup> K)
A (brick/cavity/ "Polyblox"/ plaster)	0.60	0.725	0.97	0.87
B (brick/clear cavit aerated block/ plaster)	0.65	0.77	0.78	0.79
C (brick/partially filled cavity/ block/plaster)	0.60	0.61	0.61	0.64
D (brick/retrofit cavity/brick or block/plaster)	1.63 (1) } Site 0.51 (2) } 1  0.76 (1) } Site 0.35 (2) } 2	   0.87 0.36	  0.88 0.37	1.51 (1) } Site 0.50 (2) } 1  0.93 (1) } Site 0.41 (2) } 2
<p>where (*) = the measured Λ values have been adjusted to represent the average performance of the wall</p> <p>(1) = the values represent the wall performance before insulation was injected in the cavity airspace</p> <p>(2) = the values represent the wall performance after insulation was injected in the cavity airspace</p>				
<p><b>Table 6.7.4:</b></p> <p><i>Comparison between predicted and measured transmittance values for Wall types A, B, C &amp; D</i></p>				

**CONCLUSIONS**

**CHAPTER 7**



## **7.0 Introduction**

This chapter begins with a review of the progress made in achieving the research objectives (7.1) and addresses a number of major issues which have emerged, namely, the role of the HFS measurement method as a quality assurance instrument for buildings (7.2), the relevance of design values in practice (7.3) and recommendations for future work (7.4).

### **7.1 Progress made in achieving the original objectives**

The main objective of this study has been to provide information on the in-service performance of constructions and the extent to which widely accepted prediction techniques reflect their actual behaviour. The objectives stated at the outset of the project have been substantially achieved and are summarised as follows:

- (1) To establish the uncertainty introduced by the measurement and analysis techniques adopted.

In the present study a measurement technique was established and is described in chapter 3 - section 3.3.4. The errors involved are dependent upon the particular technique adopted and cannot be looked at in isolation. They must be evaluated with respect to the method used.

Both theoretical and experimental investigations have been carried out to determine the errors involved in the measurement process. An estimate of the experimental errors and the uncertainty involved in the analysis techniques employed is given in chapter 5 and the evaluation of these errors in a field context is given in chapter 6.

In chapter 5 - sections 5.1 to 5.4 the errors were partitioned into 3 types namely, (1) physical measurement errors resulting from the calibration of the sensor sets, the way the sensor sets are attached to the wall surface and the boundary conditions to which they are subjected, (2) data processing errors and (3) data analysis errors.

Although evaluation of the errors on an individual basis was possible, combining the separate components in order to obtain an overall error was problematic since the errors were a mixture of random and systematic types. Adjustments were made for the systematic errors resulting from the calibration of the sensor sets and the way they were attached to the wall surface (sections 5.1.1 and 5.1.2). Adjustments were not possible for the boundary conditions where the estimate of the error for the worst case condition was of the order <10% (section 5.1.3). Data processing errors were negligible (section 5.2).

The only indication of the error resulting from the analysis techniques is given from the field measurements in chapter 6 - section 6.7.1 where the upper estimate is 6%. An indication of the uncertainty involved in the determination of the transmittance value with respect to the number of the monitoring days is given in Appendix B where the analysis suggests that 4 monitoring days are enough to establish the transmittance value of the wall within  $\pm 2.5\%$ .

From chapter 6 - section 6.7 the indications are that the best estimate of the random error in the measurement process is  $\pm 8\%$  with an additional systematic error involved due to the sensors which is likely to be of the order of  $\pm 7.5\%$ . The combined estimate for both systematic and random errors for a single measurement is therefore  $\sqrt{8^2 + 7.5^2} = \pm 11\%$ . However, for multiple measurements the error is reduced to  $11/\sqrt{n}$  where  $n$  is the number of measurements. For example, in the case of each individual Site for wall type A where 9 measurements were performed the error is reduced to approximately  $\pm 4\%$  for each individual Site.

Note that the variability introduced in the measurement due to the performance of the wall is excluded in the approximate value of  $\pm 4\%$ . This value is only concerned with the variability in the measurement process itself. Therefore the number of 9 measurements may have to be increased considerably if the variability in the wall performance is high as is the case with wall type A - Site 1 (chapter 6 - section 6.7.4).

From the above it can be seen that there is general agreement between the theoretical (chapter 5) and experimental (chapter 6) estimates of the variability involved in the measurement process. The robust technique employed (chapter 3) indicated that reliable measurements can be made within measurement error limits of  $\pm 11\%$  for a single measurement.

- (2) To measure the insitu thermal transmittance of a range of wall constructions representative of both the existing building stock and new build.

Investigations were carried out into 4 generic wall types representative of a range of existing and new build constructions including clear, partially filled and fully filled cavities, each having a variety of inner and outer leafs (chapter 6).

The masonry constructions investigated performed in general as expected, when the appropriate theoretical model was applied. When poor wall performance was identified this was due to cold bridging and workmanship. Discrepancies were found between the measured and theoretical values for certain wall types which were due to the design values being calculated by using an inappropriate method. This is dealt with in more detail in section 7.3.



It was found that the practicalities of setting up the measurements caused a number of problems. For example, access to buildings was restricted and arrangements had to be made prior to entry. Finding a plain wall surface to measure (not interrupted by windows or edges) was more difficult than anticipated. Additional investigations are often needed and/or other auxiliary techniques may have to be employed to complement the HFS measurement system such as thermographic surveys, boroscopic devices and thickness probes. Undertaking field measurements proved to be a time consuming process taking up considerable financial and manpower resources.

- (3) To provide an estimate of the inherent variability in the performance of the wall construction due to factors such as workmanship.

An experimental design approach was devised to separate the variability involved in the measurement process and the variability involved in the performance of the wall (chapter 6). For all wall types there were significant differences between the measurements depending on the positions on the wall to which the sensors were attached. An indication of the variability involved in the performance of the wall was given by the spread in the individual observed values, from 4% to 39.5% depending upon the wall type. The lower figure of 4% was associated with a homogeneous layer integrated within the wall structure such as the insulation in a fully filled cavity. The higher figures of 25.5% and 39.5% were associated with unfilled cavities.

For a given wall type the differences in the observed performance may be attributed to 4 major potential causes, namely:

**Dimensional tolerances and material properties:** The uncertainty introduced by the dimensional tolerances and material properties could not be evaluated directly from the field studies in chapter 6. However in chapter 4 - section 4.4.3 approximate estimates are given of  $\pm 4\%$  for a clear or partially filled cavity and  $\pm 7\%$  to  $\pm 12\%$  for a fully filled insulated cavity depending upon the cavity width.

**Changes in material properties:** An estimate of the maximum potential change in material properties was obtained from the field results. This is approximately 6% (chapter 6 - section 6.7.1) and also includes changes in the environmental conditions at the particular measurement position as well as any differences introduced by the analysis technique.

**The wall as part of a construction:** The wall is always measured as part of a construction under a given set of uncontrolled environmental conditions. This may introduce an element of variability into the measurement which depends upon the individual wall type and constructional details (e.g. thermal bridges).

**Workmanship:** A separate estimate of the variability from this source could not be made. However, the indications in chapter 6 are that workmanship will introduce an element of variability in the transmittance measurements. Evidence for this is provided by boroscopic and photographic examination which revealed major defects (Plates 6.1.3 to 6.1.10, 6.3.1 to 6.3.3, 6.4.1).

Attempting to partition the total variability due to the individual sources is difficult. An overall variability typically of the order of  $\pm 10\%$  is expected to be introduced in thermal transmittance measurements due to combined dimensional and material properties, and changes in material properties. However, if the variability exceeds  $\pm 10\%$  there is a probability that the higher values may be attributed to either the construction or the workmanship, as is the case in the present study with wall types A and B.

- (4) To compare the measured and predicted values for the wall constructions, in order to assess the walls performance in practice.

When calculation methods are employed to predict the performance/transmittance of a wall construction a distinction must be drawn between the model used for a design calculation and models which may be used in order to provide the best estimate of the heat flow through the wall construction (to gain a better understanding of the wall behaviour). In general, for the 4 wall constructions monitored, the measured value compares favourably with the predicted value if, and only if, the appropriate theoretical model is used to establish the transmittance of the wall construction.

The indications from chapter 4 are that the CIBSE 1D value can be estimated within  $\pm 4\%$  for a clear or partially filled cavity and  $\pm 7\%$  to  $\pm 12\%$  for a fully filled insulated cavity depending upon the cavity width.

The indications from chapter 6 are that insitu measurements can be made within  $\pm 11\%$  for a single transmittance measurement with this value becoming considerably lower as the number of measurements is increased  $[(11/\sqrt{n})]$  where  $n$  is the number of measurements].

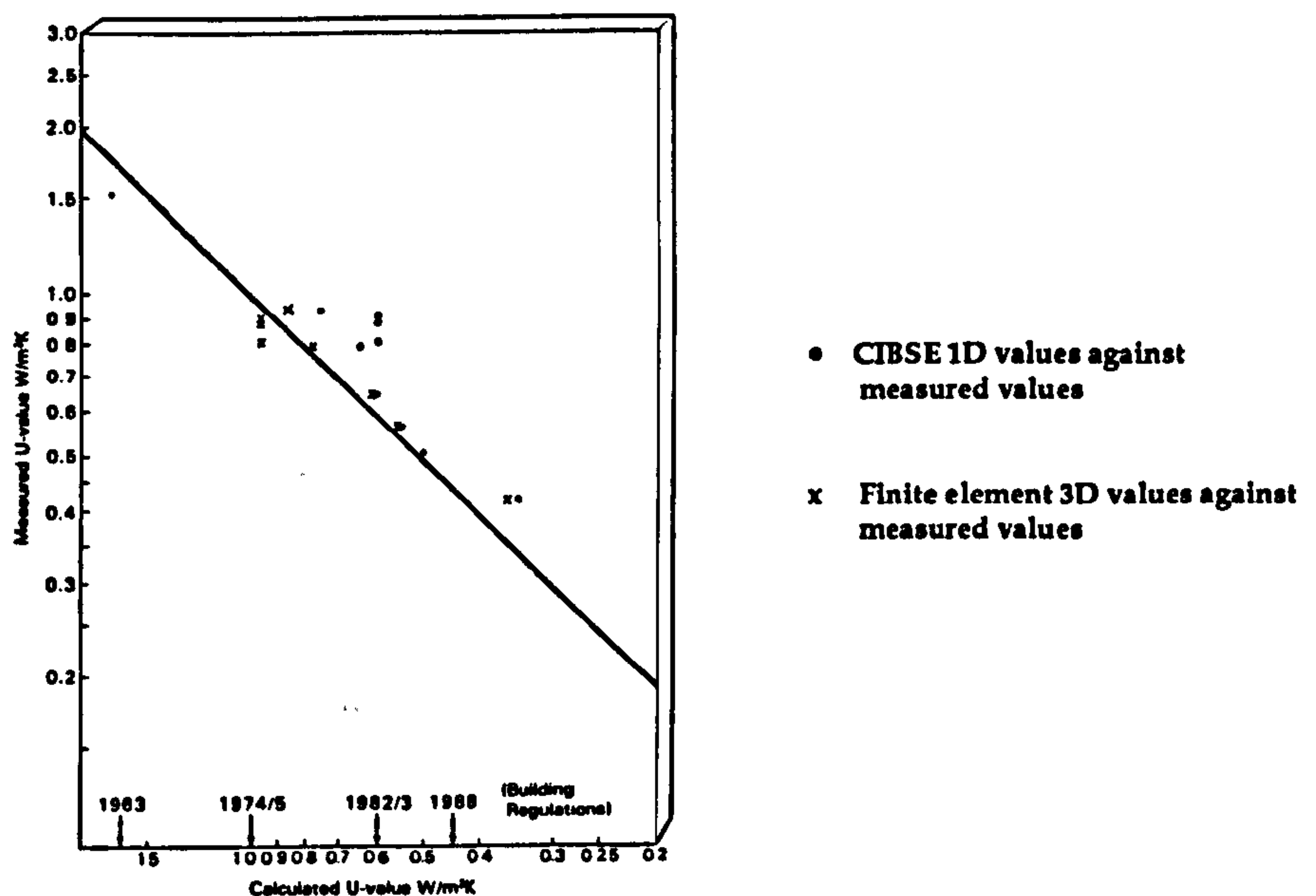
The detailed examination of the case studies in chapter 6 highlighted the difficulty of interpretation. Making a valid comparison between predicted and measured values in practice is difficult since the uncertainties in the calculation methods and the variability in the measured values have to be taken into account. The results from chapter 6 would suggest that the CIBSE 1D model is appropriate for layered constructions which are substantially homogeneous (wall types C and D), whereas the CIBSE area weighted and 3D models are suitable for non-homogeneous and/or complex wall geometries (wall types A and B).



The overall results from this study are shown in Fig. 7.1 in a form adopted by Anderson (1988). The plot is of measured values against estimated values which have been calculated by means of the CIBSE 1D model and a three dimensional finite element (FE) model. Only the means of each individual Site are presented to avoid confusion. The degree of fit between the theoretical (1D and FE) and measured values is clearly illustrated. There is good correspondence between the best estimates of the measured mean wall performance and the FE values being the best theoretical estimates. Where relatively poor correspondence resulted between the CIBSE 1D and the measured values this was due to inappropriate application of the theoretical model for wall types A and B).

This is to be contrasted in Fig. 7.2 which is Anderson's results. Here the scatter is considerably greater for the individual points shown in the plot. It is clear that the mean value for each cluster indicates a relatively poor match between the calculated and measured values. The reasons for this difference in the pattern of the results could be attributed to a number of reasons, for example, using inappropriate theoretical model and/or possible poorer control in the experimental method.

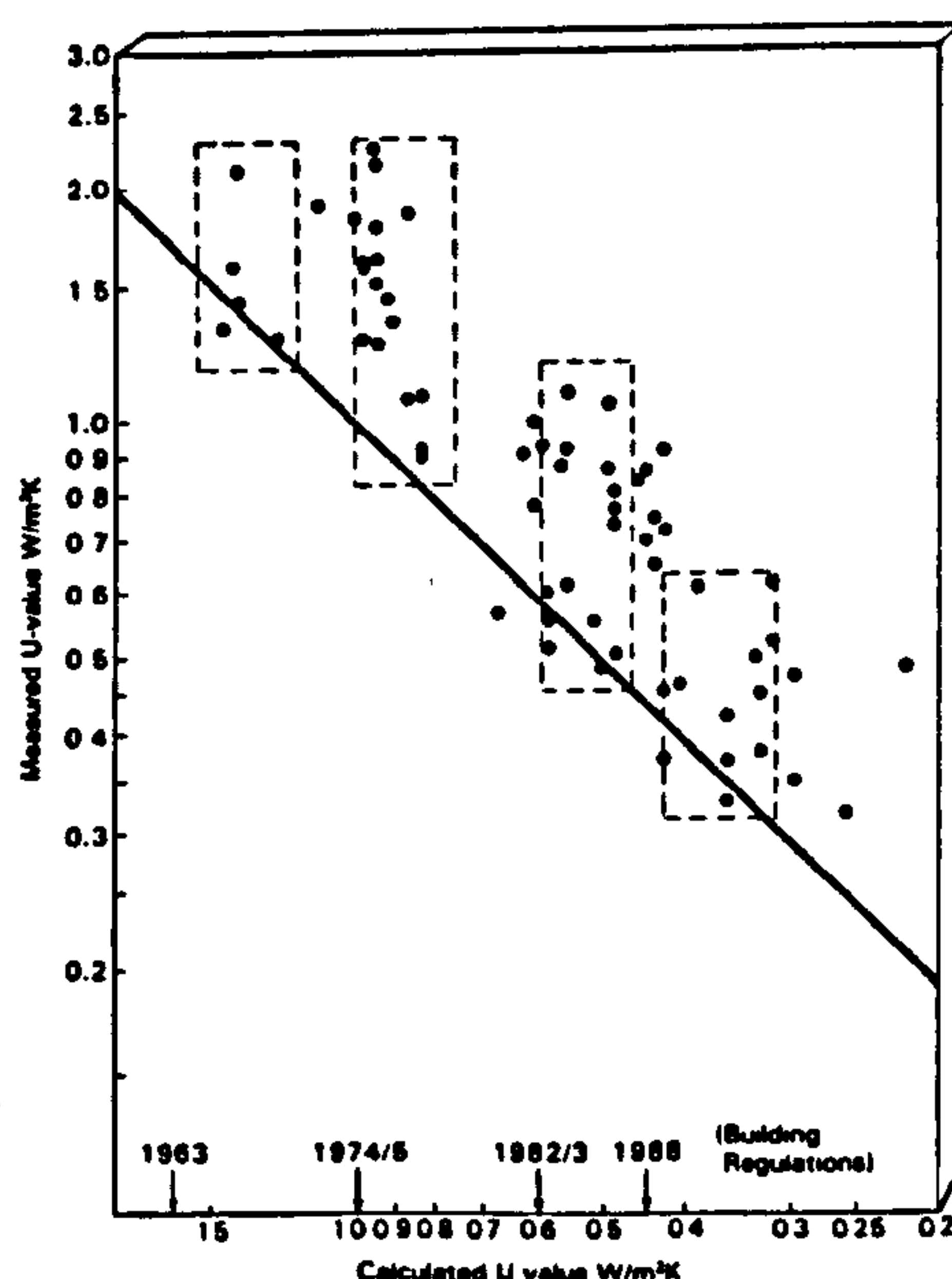
It is clear from the above that understanding the behaviour of wall constructions in practice is extremely complex. The objectives set at the start of any project involving thermal transmittance measurements must be clear in order to gain the appropriate information from the field measurements. Three approaches to an experimental design procedure were defined in the concluding section of chapter 6 - section 6.7.4. They are all capable of establishing the mean performance of the wall construction but they differ in specific aims, such as, establishing the variability involved in the measurement process or performance of the wall, or the change in the thermal transmittance value due to some change in the wall construction, such as, filling the cavity.



**Fig. 7.1:**

**Transmittance values measured on site, compared with calculated values**

The line indicates the 1:1 relationship. The maximum U values under Building Regulations are shown on the horizontal axis. The means of measured values for each individual Site are shown. The form in which the results of this study are presented is adopted from Anderson - 1988. Two calculated values are shown, CIBSE 1D and 3D finite element.



**Fig. 7.2:**

**U values measured on site, compared with calculated values**

The line indicates the 1:1 relationship. The maximum U values under Building Regulations are shown on the horizontal axis. Reproduced from Anderson - 1988. Individual values are shown. The Fig. was taken from BEPAC - 1991 (Building Environmental Performance '91), University of Kent, Canterbury, 10-11 April 1991, p. 119.



## **7.2 The role of the HFS measurement method as a quality assurance instrument for buildings**

One of the major objectives of carrying out field measurements of thermal transmittance values is to confirm/verify that the insulation system works and continues to work as anticipated. The HFS measurement method is an important and useful instrument in achieving these objectives. It may be used as a quality assurance tool for buildings where its use is defined and the need for HFS measurements have been clearly established.

However, the following suggest that the HFS measurement technique is inappropriate as a routine field test method:

A number of factors, such as, the need for skilled manpower, low utilization of equipment due to ensuring appropriate climatic conditions and the measurement time required, imply that significant manpower and financial resources are required.

The technique has significant limitations. It provides limited information about the heat flow at a particular point but where information is needed on a wider scale it is far more difficult to establish. It can therefore complement but not replace thermographic investigations.

The indications from chapter 6 are that the method is well suited for use in a research environment where the main objectives are to gain a better understanding of the wall performance (for example to establish the variability in its behaviour). In this sense the HFS measurement method is the only currently available technique.

It follows from the foregoing that to establish techniques which can be adopted as routine quality assurance field test methods for buildings it is necessary to have a combination of both thermographic and boroscopic examination, and insitu transmittance measurements. The former because of their relative simplicity, ease of use and instantaneous results. They, for example, can reveal gross deficiencies in the building fabric and enable the rapid assessment of the extent of a thermal defect to be made. On the other hand the latter can be used to verify the magnitude of the thermal defect using thermal transmittance measurements (HFSs) at selected positions.

### **7.3 The relevance of design values in practice**

In England and Wales it is standard design practice to calculate the U value using the CIBSE 1D model. This is in line with the recommendation given in the latest edition of the Building Regulations (Building Regulations - 1990):

**"When calculating U values the effects of timber joists or framing, wall ties, thin cavity closures, mortar bedding, damp-proof membranes, metal spacers and other thin discrete components may be ignored."**

Consequently, the "designed" thermal transmittance and the "actual" thermal transmittance are only expected to coincide where the above conditions exist, that is a plain wall section with uniform boundary conditions. In practice however any kind of thermal discontinuity will, to a degree, render the above invalid.

This was experienced in the present study where homogeneous and simple geometry layers had good correspondence with the calculation method, whereas poor correspondence resulted for more complex geometries since the appropriate theoretical model was not applied (Fig. 7.1). The latter is not unexpected. Given the way in which design values are calculated there is no reason to suppose that the same values will result in practice since the models underlying the calculations are not realistic of the constructions being used. It could be argued that implicit in the definition for the calculation of the U value is poor quality control as far as the designer is concerned. It enables designers to make design decisions which are not brought forcibly to their attention and which are not penalised.

The presence of cold bridging in the wall structure definitely leads to a loss of performance. From the above and indeed from the findings of the present study (mainly chapter 6) it is clear that for a wall construction to perform as designed, complete elimination of thermal bridging is ideally required.

Emphasis must be given to ensuring the required performance of the construction at the design stage. In practice, the importance of detailing at the design stage is paramount and departures from good design practice can have severe thermal repercussions. There is a need to educate and inform designers and operatives about the potential loss of thermal performance in a wall structure due to thermal bridging and workmanship defects and the benefits to be obtained from good working practices.



## **7.4 Recommendations for future work**

As a result of the work that has been carried out a series of points has emerged which needs to be addressed.

The results from this work have revealed to a certain extent that there are gross deficiencies in the wall performance in some existing forms of construction. However the sample on which the above statement is based is small in comparative terms. There is a real need therefore to extend the present work to a much bigger sample in order to establish precisely the magnitude of the shortfalls and to be able to assess how much they are costing the country in terms of energy and unnecessary production of CO<sub>2</sub>.

Deficiencies in the building fabric were mainly due to cold bridging by mortar joints which do not need to be taken into account according to the recommendations by the Building Regulations (see 7.3). It is most important therefore that the effect of cold bridging "known at the design stage" is examined carefully. A detailed modelling and measurement exercise is required so that the influence of known cold bridging (i.e. lintels), on the overall performance of the wall can be established (Dudek - 1989). In more general terms, if the wall constructions are to perform as designed, perhaps the model to be followed is the successful approach applied by the Scandinavian countries over a number of years. That is the combination of good design practices, trained site operatives and quality assurance techniques at the design, construction and post-construction stages.

As a consequence of this study it was recognised that there were difficulties when an attempt was made to predict the wall performance even with the best of the models. As far as material thermal properties and boundary conditions are concerned, suitable inputs (standard values) were used in the models employed in the present study, but the models are sensitive to all input values, such as htc values, values used for the cavity airspace. Further research is required in this area before they can be used with confidence.

In general, differentiation must always be made between simple and complex models. The more complex the model the greater are the number of assumptions relating to boundary conditions, contact resistances, etc., which need to be made. An obvious drawback in any complex computer model is that since the heat transfer processes are treated in greater detail, they may also be accompanied by an increasing level of uncertainty due to the selection of the appropriate boundary conditions. There is a need to study in greater depth the variability in boundary conditions and air-movement in the cavity airspace for example, and the way in which they may influence the resulting transmittance value.

In building up a better understanding of how walls behave in practice there is a need to compare theoretically predicted values with measured results. However there are cases where substantial differences between the two values may arise and the interpretation of the results becomes complicated. Cases such as these highlight the distinct and immediate need for a greater integration between theoretically predicted values by means of simple manual calculation models such as the CIBSE 1D and more sophisticated models such as 3D FE modelling packages with measured results. The task of carrying out laboratory and field experiments must be undertaken in parallel in order to provide enough detail to guide model development that will ultimately lead to better models and better agreement between prediction and measurement.

A combined approach such as this will certainly lead to an increase in knowledge and a better understanding of the building heat transfer phenomena and the behaviour of the building fabric. It will also build up confidence in the measurement and modelling techniques. The work must therefore go beyond purely experimental or purely analytical/modelling work. Both approaches must be strongly integrated in unified programs of work, if research results are to be applied with confidence in order to guide design.



# APPENDIX A

## **Finite element technique**

The finite element technique is a numerical analysis technique used for obtaining approximate solutions to a wide variety of engineering problems. It is the representation of a body or a structure by an assemblage of subdivisions called finite elements, which are interconnected at junctions and are called nodes or nodal points.

Nodes usually lie on the element boundaries where adjacent elements are considered to be connected. In addition to boundary nodes, an element may also have a number of interior nodes. The nodal values of the field variable and the interpolation functions (the approximating functions sometimes are called interpolation functions and are defined in terms of the values of the field variables at specified points which are the nodes) for the elements completely define the behaviour of the field variable within the elements.

For the finite element representation of a problem, the nodal values of the field variable become the new unknowns. Once these unknowns are found, the interpolation functions define the field variable throughout the assemblage of elements.

Clearly, the nature of the solution and the degree of approximation depend not only on the size and number of the elements used, but also on the interpolation functions selected.



## **APPENDIX B**

## **Data analysis techniques**

In this appendix three issues are addressed that are relevant to the analysis techniques.

- (1) A validation exercise for the computer model used in the present study based on the data provided by Anderson (Anderson - 1985).
- (2) The degree of correspondence between the two analysis techniques used in the study namely, the Averaging and the Anderson methods.
- (3) The uncertainty limit involved in the determination of the  $\Lambda$  value with respect to the number of monitoring days.

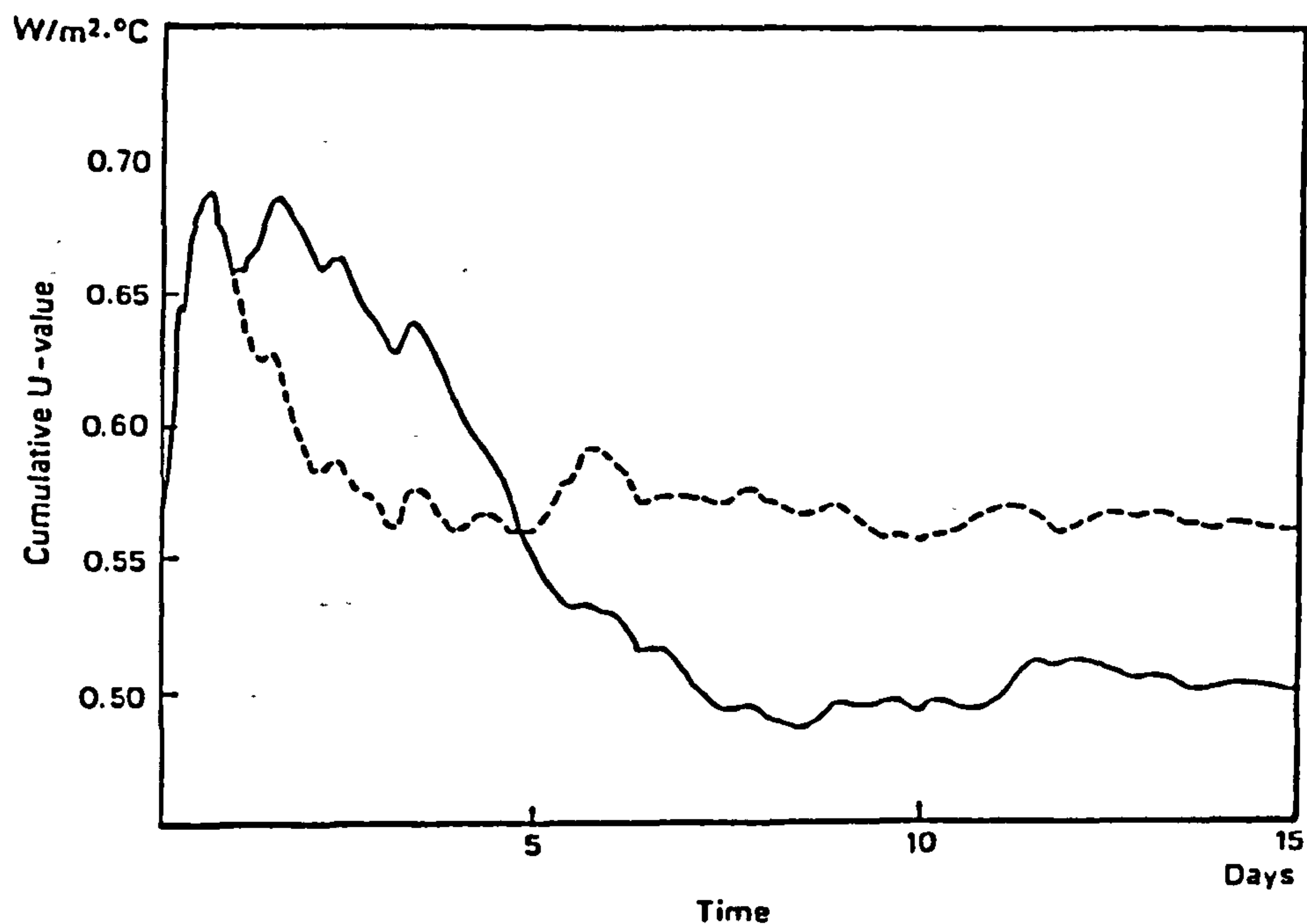
In order to ensure that the computer model of the Anderson technique was correctly implemented a validation exercise was carried out. The original data (Anderson - 1985) were requested from the Scottish BRE which consisted of internal/external air temperatures and heat flow readings (Fig. B.1). The data was interpreted using a computer program developed for this study at Newcastle and the shapes of the original graphs presented in Fig. B.1 showing the Averaging and the Anderson transmittance values for a brick wall with cavity fill were recovered in Fig. B.2. The graphs were compared and were found to be exact match.

An issue of major concern in the present study was whether the two methods of analysis produced consistent results. This was addressed in chapter 6 where for each Site the correlation coefficients were computed for the two methods for wall types A, B and C. The results are presented in Table B.1 where it can be seen that the correlation coefficients are high ( $>0.96$ ) which suggests that there were no overall significant differences between the two methods of analysis used. In addition the maximum difference between any single conductance value derived using the two methods was 7.7% (Table B.1).

A study to establish the uncertainty involved in the determination of the conductance value with respect to the number of monitoring days was carried out using a long term field data set. This was for Site 1 - wall type A. The sequential analysis was carried out as follows: 0-2 days, 0-4 days, 0-6 days, .....up to 0-42 days. The data used were taken from a stable HFS. The results for the Averaging and the Anderson transmittance values are presented in Fig. B.3 where the points shown on the plots are at the end of a 2 day period. Both values have been calculated by averaging the last 96 values (24 hrs).

Fig. B.3 indicates that in this case the Averaging method stabilises earlier (after 8 days) than the Anderson method and that 4 days are enough to establish the  $\Lambda$  value of the wall within  $\pm 2.5\%$ . As expected, as the number of monitoring days is increased, the error band narrows for both methods as they seem to converge towards the "true" value. However it was decided to carry on the measurements for 12/14 days which is the average monitoring period for the present study in order to ensure the robustness of the results. It would be interesting therefore to carry out the same exercise for every data set so that the minimum possible monitoring time could be established with confidence.

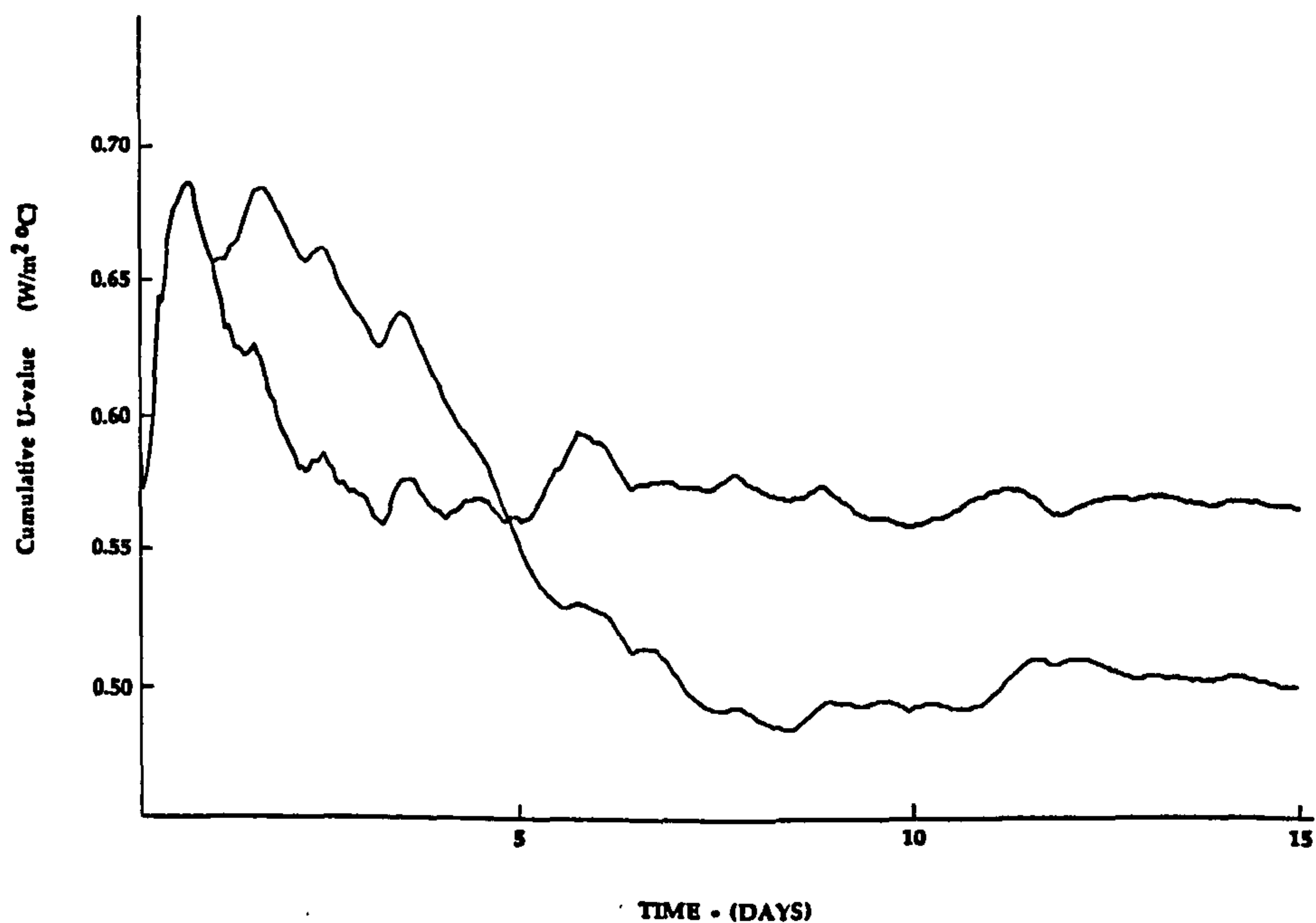




**Fig. B.1:**

Cumulative U value for brick wall with cavity fill:

uncorrected for changes in internal and external temperature (solid line),  
and corrected (broken line) (After Anderson - 1985)

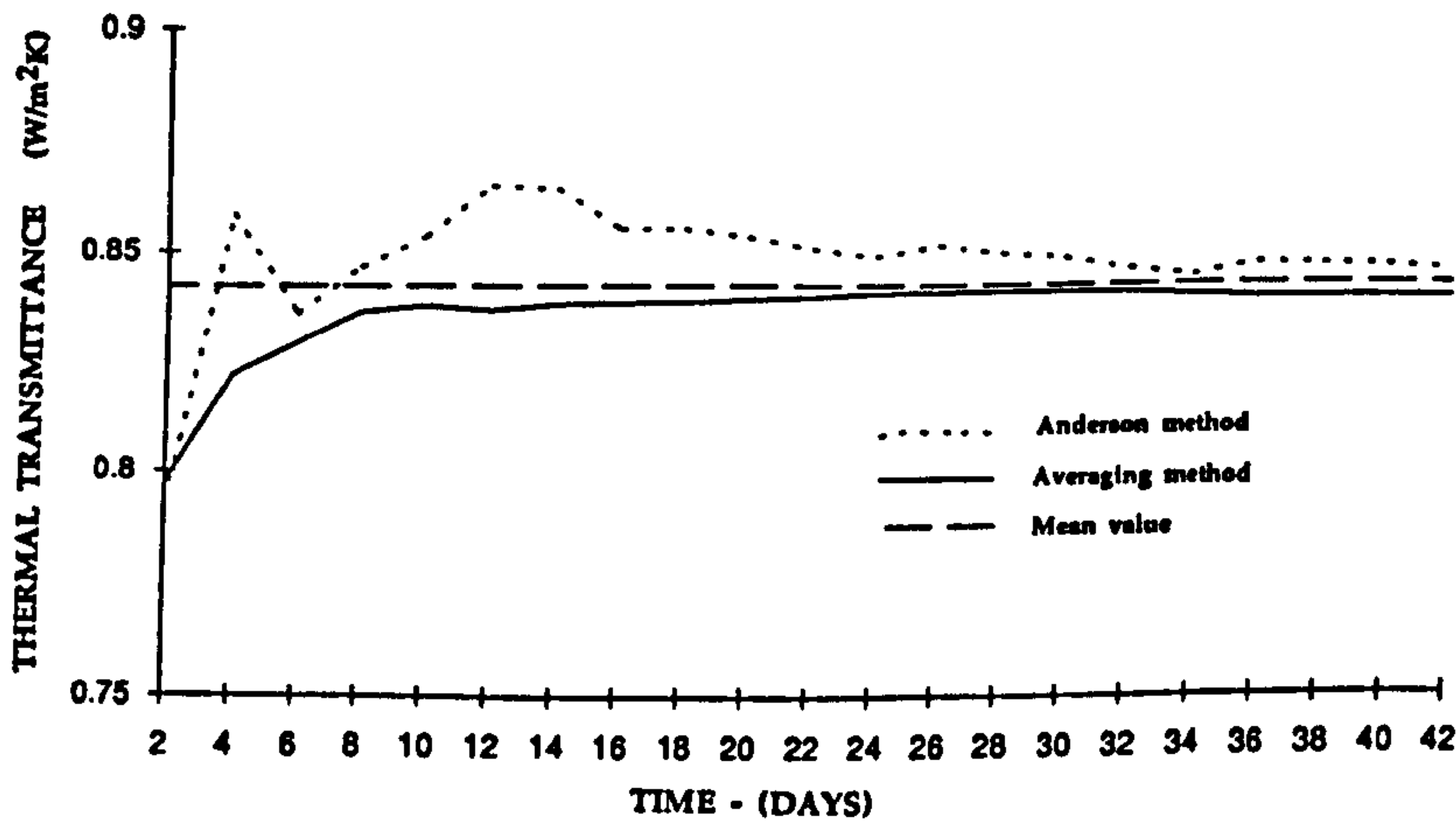


**Fig. B.2:**

Cumulative U value for brick wall with cavity fill:

Validation exercise. The original graphs presented in Fig. A.1 above  
were recovered from the data requested from the Scottish BRE.

Wall Type (Construction)	Correlation Coefficients	Maximum difference between the two methods for a single value
<b>A</b> (brick/cavity/"Polyblox"/plaster)	Site 1: 0.9976 Site 2: 0.9759 Site 3: 0.9630	2.65% 3% 3%
<b>B</b> (brick/clear cavity/aerated block/plaster)	Site 1: 0.9995	3%
<b>C</b> (brick/partially filled cavity/block/plaster)	Site 1: 0.9882	5.6%
<b>D</b> (brick/retrofit cavity/brick or block/plaster)	Site 1: — Site 2: —	4.4% 7.7%
<p><b>Table B.1:</b></p> <p><i>Correlation coefficients and maximum difference values for the two methods for wall types A, B, C and D</i></p>		



**Fig. B.3:**

*Transmittance values for the Averaging and the Anderson methods.  
A long term field data set was used from wall type A - Site 1.  
The graph indicates that 4 monitoring days are adequate to establish  
the  $\Lambda$  value of the wall within  $\pm 2.5\%$ .*



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